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Bearings & Bearing Metals

Mechanical Engineering

M. E.

1909

BEARINGS AND BEARING METALS

BY

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B. S. University of Illinois, 1903

THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MECHANICAL ENGINEER

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1909

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

May 1, 1909

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

WILLIAM VAN DUNKIN, B.S., 1903

ENTITLED BEARINGS AND BEARING METALS

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF MECHANICAL ENGINEER

In Charge of Major Work

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on
Final Examination

B E A R I N G S

A N D

B E A R I N G   M E T A L S

C O N T E N T S.

PART I.

PART II.

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P A R T I

B E A R I N G S .

INTRODUCTION

The subject of Bearings and of Bearing Metals in particular is one concerning which a wide variety of opinion exists if we may judge from the literature existing on the subject. This is due, in part, to experimental data which is often contradictory and also to widely different conditions of service to which any bearing metal may be subjected. These conflicting opinions may be the result of a lack of a standard basis for comparison to which data may be referred or to the various conditions under which tests were made. The service test is the only one giving exact information and yet such tests may give results varying greatly. Laboratory tests give, in general, only comparative results which may be of considerable value. In a service test, the test itself is auxiliary to the work in hand. Therefore, accurate data can not always be obtained. Hence, any conclusions reached by a consideration of such data is likely to be more or less conflicting.

The importance of the subject, however, is such that reliable methods of testing approximating as nearly as possible, actual service conditions should be used. A consideration of the fact that from 20 to 50 per cent of the power generated for manufacturing purposes is used up in overcoming the friction developed in the bearings of the overhead shafting, to say nothing of the power thus consumed in the bearings of the various machines themselves; or that from 10 to 20

per cent of the power developed in the engine itself is consumed in overcoming principally its own journal friction, will at once indicate the importance of the subject. Very little is known of the power required to overcome the friction of various classes of machinery used in mills and factories, but it is safe to say that the work usually expended in the actual operations which the machinery is intended to perform must be a small fraction of the power developed by the engine itself. Not all the loss is in the bearings but by far the greater part of the loss is here. It is evident, therefore, that there is much room for progress in the reduction of some of these sources of loss by more careful attention to the laws of friction and particularly to more scientific methods of lubrication.

The purpose of testing is to find what metal or combination of metals gives the best results in service. Friction is not the only consideration. Indeed, it is only of minor importance. Other properties such as resistance to heating, wear, cost, etc., are of particular importance. With improved methods of lubrication and by this is meant a lubricating system which insures a copious supply of oil under all conditions to the bearing, the friction between the two parts is very little. It thus appears that a knowledge of the other properties of bearing metals are desirable and indeed, required if progress is to be made in finding a more suitable bearing metal than is now known. New combinations of metals with various methods of heat treatment are contin-

ually appearing, some possessing value above others as a bearing metal, some possessing no value. It is probably true that the limit of perfection is about reached with the particular form of bearing now in use. The discovery of some new combination of metals forming new alloys, together with some special method of treatment may give us a better bearing metal alloy than we have at present. The advent of the ball and roller bearing has done more than any other single process or practice of engineering to reduce lost work and increase the speed and economy of modern machinery. The expense, however, prevents them from coming into more general use. There is no doubt but what their application to bearings for line shafting, engines, etc., while increasing somewhat the first cost, would result in a very material reduction in operating expenses.

In this thesis is presented no new device or arrangement to take the place of existing designs or patterns of bearing metals. The purpose has been to collect many of the latest facts existing regarding the use of bearings also some of the tests that have been made with the conclusions reached. It is, perhaps, needless to add that the source from which this information has been drawn is very largely the technical journals.

No deductions or conclusions are made from the consideration of the facts as herein presented. Certain so-called facts, however, which seem to be only partially confirmed experimentally, or conclusions made from data

either defective or insufficient, have been noted and given as the subjects for further investigation and study.

The thesis itself is divided into two parts. The first part deals particularly with friction, lubrication and design of bearings. The second part deals entirely with bearing metals and bearing metal alloys.

F R I C T I O N

Unlubricated Surfaces

To obtain the proper proportions for a journal and its bearing, in order that they may run cool and with the least wear, is one of the most important problems in machine design. The question of heat and of wear is one of friction which may be defined as the force tending to prevent the relative motion of two bodies in contact. This resistance to relative motion is due either to abrasion or molecular interference. No matter how smooth the contact surfaces may be, they show when examined under the microscope, projections and depressions, so that when in surface contact the projections and depressions of one surface fit irregularly with the depressions and projections of the other surface. When relative motion takes place a leveling or tearing down of these projections occur. Further, the molecules themselves are constantly vibrating about their mean position so that if the projections be not torn away the intermingling of the molecules of the two bodies in contact give rise to a resistance to relative motion. Such a process is not easily reducible to any regular system of laws; but certain generalizations, however, may be made that are useful to the engineer.

To cause a body of weight W to slide along a horizontal plane with uniform motion, there will be required a force P acting parallel to the plane. The ratio $\frac{P}{W}$ is called the coefficient of friction. Similarly if a journal revolving in a bearing under a load W requires a force F acting tangentially

at the surface to produce uniform turning then the ratio $\frac{F}{W}$ is called the coefficient of friction. This coefficient is usually denoted by μ.

Laws of Friction

1 - Within certain limits, friction is proportional to the pressure and independent of the extent of surface over which the pressure is distributed; but upon an increase of pressure per unit area, the friction increases at a greater rate than the load. This is equivalent to saying that the coefficient of friction increases with the pressure or load.

2 - The coefficient of friction varies with the speed of the rubbing surfaces, and is greatest when motion is just beginning.

3- The friction of solids and liquids diminishes as the temperature increases due to the fact that abrasion is less difficult at higher temperatures. For gases, however, friction increases as the temperature rises.

LUBRICATED SURFACES.

Frictional Resistances Due to Viscosity

When a journal is at rest in its bearing, the point of contact is along a narrow strip at the bottom. When rotation begins, the journal tends to roll upward on the bearing until contact is no longer at the lowest point of the journal but at some point higher up on the surface of the bearing. When oil is introduced into the clearance space between the journal and its bearing, the area of the contact is lessened and if certain conditions, regarding speed and pressure obtain,

direct contact between these parts no longer exists. When the two parts are not in contact but are separated by the oil film the resistance mainly to relative motion is due to the friction between the successive layers or rings of oil moving in contact with each other. The outer layer of oil is in contact with the bearing and the inner layer is in contact with the journal. The resistance, therefore, to relative motion will depend upon the viscosity of the oil. By viscosity is meant the shearing stress developed in the fluid while undergoing distortion, and the shearing stress divided by the rate of distortion is called the coefficient of viscosity or more frequently the viscosity of the fluid. Two parallel planes at a distance y apart have a relative speed of v feet per second. If the space between these planes is filled with oil in motion in a direction parallel to the planes and the relative motion of the successive layers varies uniformly from rest to v feet per second, it can be shown that the resistance to relative motion per unit area is $K\frac{v}{y}$, In the case of journals the contact area is π dl and the total resistance is therefore

$$\pi dlk\frac{v}{y} \qquad (1)$$

In this formula

d = diameter of journal
l = length of journal
k = coefficient of viscosity

The resistance or friction, therefore, is independent of the load on the journal but varies directly as the area of the oil in contact with the journal, the coefficient of viscosity and the speed; and inversely as the thickness of the oil film. So far, we have assumed that the journal is con-

centric with the bearing, a fact which is true only at extremely high speeds. Concentricity is approached very nearly at speeds such as are common in certain steam turbines. The amount of eccentricity depends upon the speed and the load becoming less for any given load as the speed increases. Since the friction varies inversely as the thickness of the oil film, we have the friction of the journal decreased on the side of the thick oil film and increased on the side of the thin oil film. Osborn Reynolds has shown mathematically, that the increase in friction due to the thinning of the oil film is greater than the decrease of friction due to the thickening of the oil film. The friction, therefore, increases with the eccentricity and hence with decreased speeds. However, according to the law stated above in (1) the friction increases with the speed; but as the speed increases the temperature of the oil rises and the viscosity of the oil decreases. The effect of these changes acting simultaneously is at first to diminish friction to a certain minimum value. Beyond this point if the speed continues to increase, the friction also will increase but probably not directly with the speed.

In Figure 1 are shown several curves illustrating the variation in the relative viscosity of several oils with the temperature. With a rise in temperature the viscosity decreases, the rate of change being more rapid at the lower temperatures. It will be noticed, also that the viscosity approaches a common value at about the temperature of boiling water. This also indicates greater variation in friction at lower temperatures.

Friction of Oily Surfaces in Contact.

In the case of a journal rotating in its bearing, the friction due to the interference of the projecting particles of one surface by the particles of the other surface is reduced if the surfaces are slightly oily or greased. As long as the parts are in contact the nature of the friction is the same as that of unlubricated surfaces. Three conditions arise either one of which may bring about contact between the oily surfaces: (1) excessive bearing pressures per square inch of projected area; (2) insufficient oil supply, and (3) low rubbing speed. Contact between the journal and its bearing is to be avoided in practice wherever possible. When contact does occur a large amount of work is wasted. This work appears as heat and soon destroys the bearing or causes the journal to expand and to grip the bearing.

Coefficient of Friction.

For oily surfaces, the coefficient of friction, as given for unlubricated surfaces is only approximate. It is very close at high pressures and low speeds. Thurston shows the following for a journal tangent to its bearing (loose fitting).

$$\text{Force of Friction} = F = \frac{fW}{\sqrt{1 + f^2}} \qquad (2)$$

where W equals the load on the bearing.

f = coefficient of friction for the unlubricated surfaces,

and, F = the tangential force required to keep journal rotating uniformly,

also $F = \mu W$ in which μ is the coefficient of friction. Substituting this value in the above equation, and solving for μ

we have

$$\mu = \frac{f}{\sqrt{1 + f^2}} \text{ - - - - - - - - - - - - - - - } (3)$$

For a tightly fitting journal

$$F = \begin{cases} \text{From } 1.27 \text{ f W} \\ \text{to } \quad 1.57 \text{ f W} \end{cases} \text{ - - - - - - - - - - - - - } (4)$$

Hence

$$\mu = \begin{cases} \text{From } 1.27 \text{ f} \\ \text{to } \quad 1.57 \text{ f} \end{cases} \text{ - - - - - - - - - - - - - - - } (5)$$

Taking the value f as .033 as determined experimentally by Morin, equations (5) and (8) may be written.

For loosely fitting journals

$$\mu = .0298 \text{ say } .03 \text{ - - - - - - - - - - - - - } (6)$$

For tightly fitting journals

$$\mu = \begin{cases} \text{From } .0419 \text{ say } .04 \\ \text{to } \quad .0518 \text{ say } .05 \end{cases} \text{ - - - - - - - - - - } (7)$$

In general this kind of friction does not exist in horizontal bearings, well designed and cared for; however, thrust bearings appear to develop this kind of friction.

<u>Film Friction</u>.

When a journal rotates in its bearing, a layer of oil adheres to the surface of the rotating part. As motion continues the journal brings up more oil than can be crowded into the space between it and the bearing. Some oil is, therefore, forced out sideways in the bearing. The oil, resisting this action because of its viscosity, will support the journal away from contact with the bearing. The journal in this condition assumes an eccentric position in its bearing and is therefore, separated from the bearing by a wedge shaped mass of oil. Tower proved experimentally and Reynolds mathemati-

cally, that the condition of pressure between a journal and its bearing is as shown in Figure 2. The ordinates to the curve mc"n represent the pressure at the given points in the diametral section of the journal. The greatest pressure is seen to be on the "off" side of the center. The pressure at a' may decrease to nothing or even become negative. It will be seen that the oil film is thinnest at a point somewhat farther on in the direction of rotation from the point of external application of the load.

If the pressure at m decreases to nothing or becomes negative, the oil film is destroyed and the greasy surfaces of journal and bearing are in contact. The resulting friction, therefore, is that of oily surfaces in contact.

The stability of the oil film is a function of the pressure and consequently of the load on the bearing. Also as the oil is wedged in between journal and bearing the upward pressure or force exerted by the oil would be directly proportional to its density and the square of its speed. Further, since the temperature of the oil depends on the speed of the journal, the viscosity of the lubricant will be an inverse function of the temperature, and, therefore, of the velocity. Mr. H. F. Moore gives the following equation for the stability of the oil film

$$p = kv^n \qquad (8)$$

in which p equals bearing pressure per square inch of projected area of journal,

v equals speed of rubbing,

k and n are constants depending upon the kind of oil.

From tests on vacuum engine oil (ordinary machine oil) Mr. Moore found values for n and k to be 0.5 and 7.47, respectively. Substituting the values in equation (8) we have for the breaking down of the oil film the unit pressure

$$p = 7.47\sqrt{v} \quad \text{- - - - - - - - - - - - - - -} \quad (9)$$

It is likely that these constants would not be materially changed for the various oils ordinarily used. The values of these constants, however, should be determined experimentally for several of the various commercial oils.

<u>Laws of Film Friction</u>.

Values of the coefficient of friction obtained by Stribeck (Z. d. V. d. Ing., Sept. 6, 1902) are given in Figure 3. He used a Sellers bearing composed of gun metal and having double ring lubrication. The dotted curves are from Heiman's report (Z. d. V. d. Ing., Vol. 49, p. 1161). They refer to a solid bush of gun metal in which was perfect film lubrication. In the Sellers bearing the brass extended only half way around the journal, consequently the action of the lubricant was probably somewhat different in each case, which may in part account for the variation in the two sets of curves.

From equation (1) we have

$$F = \frac{\pi d l k v}{y} \quad \text{or}$$

$$\mu = \frac{F}{W} = \frac{\pi d l k v}{y\ w} = \frac{\pi k v}{y\ p} = c\frac{v}{p} \quad \text{- - - - - - - - -} \quad (10)$$

Equation (10) shows that μ varies directly as the speed and inversely as the unit bearing pressure when the temperature of the oil is constant and the oil film of uniform thickness around the journal.

Referring to the dotted curves in Figure 4, it is seen that μ is not proportional to the speed even when the temperature of the bearing is constant. Between 20 feet and 75 feet per minute, μ increases less rapidly than the speed due to the increase in the temperature of the oil. The value of the coefficient of viscosity of the oil decreases with an increase of temperature. Hence, as the speed increases μ falls away from the simple linear law.

For speeds below 20 feet per minute, the change in μ is exactly proportional to the speed, but as the speed decreases the eccentricity increases until finally contact between journal and bearing occurs with the result that the laws of friction are those for lubricated surfaces in contact. The curves, therefore, reverse and the coefficient of friction attains a minimum value. The point of minimum friction is important, since in design, speeds and bearing values should be avoided which tend to bring about this condition.

Figure 4 (Heimann's experiments) shows the variation in coefficient of friction and the various positions of the minimum points for given temperatures in bearing.

At low speeds, the curves all rise rapidly and they tend to converge at the constant value 0.15, the coefficient of friction of greasy metals sliding on each other, long ago determined by Morin.

Intermediate Friction.

A third class of friction is mentioned by Mr. H. F. Moore and called by him intermediate friction. A strict

mathematical analysis, or an experimental study of this kind of friction is not readily made on account of the number of variables to be considered.

Any method of lubrication which results in a diminished supply of oil probably brings about failure to maintain a perfect oil film. Also increasing the pressure on the bearing beyond certain limits (Equations (8) and (9)) changes the friction of perfect oil film lubrication to friction of lubricated surfaces.

For speeds varying from 80 feet to 250 feet per minute and pressures not exceeding 300 pounds per square inch of projected area, Moore found μ to lie between .01 and .02. These values confirm results obtained by Kingsbury and Tower.

On account, however, of the many and various conditions arising in this kind of friction, no definite values can be given to μ, but for purposes of design and to keep bearing pressures down within the limits of pressures used in practice μ may be taken as equal to .02.

The Influence of the Lubricant.

The object of lubrication is to reduce to as small a quantity as possible the friction between two surfaces which are moving or rolling on each other. Another object is to reduce to a minimum the wear between the surfaces. Friction means so much lost work, hence the importance of reducing it to a minimum.

The coefficient of friction as we have seen, varies most with low speeds and low unit pressures, and temperatures

when different kinds of lubricants are used. For continuous work, however, at higher unit pressures and temperatures the change in the coefficient of friction is so slight as to become negligible.

However, in determining the force required to start a machine, or in considering machines working intermittently some allowance in the coefficient of friction must be made.

Influence on the Coefficient of Friction of the Manner of Delivery of Oil to Bearing.

The coefficient of friction is not materially changed by the manner of delivery of oil to bearing, so long as the oil actually reaches the surface of the bearing. The kind, or method of lubrication to be used will, therefore, depend upon the pressure and temperature or journal speed. For high pressures and continuous loading, forced lubrication must be used; as for example in bearings for heavy dynamos and flywheels. The limits of bearing pressure, at which forced lubrication should be chosen as preferable to other forms of lubrication are not clearly defined. The speed, clearance and whether or not the oil is to carry away part of the heat due to friction, are all to be considered. Thus for slow speeds drop lubrication may be used since the heat generated, due to the work of friction, is small, but the higher the speed the greater the work of friction, consequently ring or collar lubrication must be used in order that greater quantities of oil may be made to pass through the bearing in order to carry away some of the heat generated by friction.

The Point of Delivery of Oil.

Referring to Figure 5 which shows the distribution of pressure around a journal, we are enabled to determine the best position in the circumference of the bearing for introducing the lubricant. Evidently this should be at the point of least pressure. When the speed of rotation is slow the pressure is greatest at p, which is just before the point of nearest approach of journal and bearing. Beyond this point in the direction of rotation the pressure falls to nothing and may become negative. Experimentally it has been found that at this point oil may under certain conditions, be drawn up through a pipe from a reservoir at least 6 inches below the point of least or negative pressure. As is shown by the curve, the pressure soon rises and is maintained fairly uniform around the journal.

As the speed of rotation increases, the pressure of the oil decreases and the position of greatest pressure p, recedes from B toward the bottom of the journal. At the same time, the point of zero pressure advances toward the top of the journal. The point of nearest approach between journal and bearing still remains at B. With an infinite speed of rotation, the points of greatest and zero pressure would be at the top and bottom of the journal.

It would appear, therefore, that the lubricant should be introduced to surface of bearing at the point of lowest pressure, especially when automatic methods of lubrication are employed. In general, automatic means of oiling bearings are unsatisfactory as the oil may not readily reach that point of

the bearing under greatest pressure owing to the more or less vibratory motion of the point of zero pressure around the journal.

For forced lubrication, that is, where the lubricant is introduced by mechanical means at a fixed rate and at a given pressure; the oil should preferably be introduced at the points of highest oil pressure.

Influence of the Speed on the Coefficient of Friction.

For a constant temperature and pressure the coefficient of friction increases at first as the speed is increased. With further increase of speed the coefficient decreases more slowly as the speed continues to increase. Recent experiments show the coefficient of friction attains a maximum value for speeds ranging from 30 feet to 45 feet per second (Tr. and Tr., Vol. 6, p. 42). Stribeck found that for speeds not exceeding 8 feet per second, μ increased as the square root of the speed, For values between 8 feet and 13 feet per second the increase in μ is less rapid. The results obtained for μ by experimenters are somewhat contradictory. Perhaps Thurston's value is as good as any. For speeds up to 18 feet per second, he found μ to vary as the fifth root of the speed. Beyond 18 feet per second, the value of the coefficient of friction is not materially changed by an increase of speed, and for practical purposes may be considered constant.

Influence on the Coefficient of Friction of the Pressure per Square Inch of Projected Area of Bearing.

The experiments for determining relation between

bearing pressure and coefficient of friction range from 14 pounds to 215 pounds per square inch and in temperature from 72° to 212° Fahr. The journal speed was constant at 30 feet per second, (Tr. and Tr., Vol. 6).

The coefficient of friction decreases as the pressure increases. The equation expressing the relation between p and μ is

$$p\mu = .568 \text{ - - - - - - - - - - - - - - - - } (11)$$

This equation applies roughly to all materials experimented upon which were for the journals, steel, nickel steel and mild steel and for the bearings, white metal, mercury amalgam and gun metal.

Equation (11) may be written

$$\mu = \frac{.568}{p} = \frac{F}{P} \text{ or}$$

$$\mu P = F = .568 \frac{P}{p} = .568 A \text{ - - - - } (12)$$

in which

F = force of friction in pounds

P = load on journal, and

A = projected area of bearing.

This equation shows that the force of friction increases directly as the area of the cross-section increases. If the load on the journal remains constant and the area of the cross section is increased, the result is a decreased unit bearing value. That is, the force of friction is increased for from equation (11) μ varies inversely as the unit pressure.

It appears, therefore, that to use a bearing as long as possible, and a shaft as large as possible is not an advantage. However, the work of friction may be reduced by keep-

ing as small as possible the shaft diameter. In high speed bearings the shaft is made long on this account.

The Influence of the Temperature on the Coefficient of Friction.

The effect of an increase in temperature of bearings is to reduce the viscosity of the oil. This leads to a reduction in friction (equation (1)). On the other hand, the least thickness of the oil film is reduced which leads to an increase in friction.

For a given speed and pressure, the coefficient of friction decreases as the temperature increases. Considering the limits of temperature ordinarily attained in practice - about 100° Fahr. to 212° Fahr. the following equation gives very closely the relation between p, μ and t.

$$p\mu\,(t - 32) = 51.2 \qquad (13)$$

The Effect of the Composition of the Bearings on the Coefficient of Friction.

So long as bearing receive s an abundant supply of oil, the coefficient does not appear to change materially by using different materials for bearings. Bearings, composed of metals or alloys that may under certain conditions, seize at a low pressure per square inch, have been run without causing any trouble at more than 3000 pounds per square inch. It thus appears, that at these high pressures, as long as the bearings remain cool, the surface of the bearing and journal are separated by films of oil. The friction, therefore, is of the nature of fluid friction and is, practically, independent of the kind of material forming the bush or bearing.

Figure 7 shows the variations in μ for three kinds of bearing materials, gun metal, white metal and mercury amalgam. The gun metal bearing gave a slightly lower coefficient than white metal but the difference is slight. It may be said therefore, that the nature of the materialin bearing, if of good quality exercises very little influence on the coefficient of friction. But at slow speeds and with imperfect lubricating devices the value of μ might change very considerably. This matter might with profit be further investigated experimentally.

Recently many alloys, specially treated have been brought out the claim for which is that they give a lower value of μ. One of these, made by an English manufacturer is described in The Mechanical Engineer, Vol. 18, p. 365. Tests made on the alloy before being treated and after being treated show that 12% less power is absorbed in the treated bearing than in the untreated bearing.

The Effect on the Coefficient of Friction of the Material Forming the Journal.

For all practical purposes, the material forming the journal has no effect on the values of μ. Figure 7 shows the variation in the coefficient of friction for journal composed of carbon steel, mild steel and nickel steel. The nickel steel is lower but not strikingly lower than the others.

The Effect on the Coefficient of Friction of the Shape and Arrangement of the Oil Holes.

No data and results exist, so far as could be found on the change in μ for the various forms and arrangement of the

oil grooves. The purpose of the oil groove is to distribute the oil over the bearing. If this is not done μ will increase due to lack of lubrication. The oil film may easily be rendered unstable by improper design and location of the grooves. In general, the oil grooves should be made spiral, starting from a point at which the oil is received and ending near but not at the outside rim of the bearing. A return series of grooves should be run in an opposite direction to the first series of grooves in order to deliver part of the oil to the center of the bearing.

Influence on the Coefficient of Friction of Clearance between Journal and its Bearing.

A relatively high turning force is required to rotate a journal in a snugly fitting bearing even when the unit pressure is quite low. The friction to be overcome is that between shaft and oil, the particles of the oil against each other, and the oil and the bearings. Tests reported in Tr. and Tr., Vol. 6 show how the total frictional force at circumference of journal is dependent on unit pressure and clearance. With pressure equal to about 15 pounds per square inch the force of friction decreased rapidly with an increasing clearance up to about .06" when the force of friction remained practically constant. For the higher pressures - 150 pounds to 225 pounds per square inch the force of friction steadily decreased with increasing clearance.

The following test shows the influence of clearance on the rise in temperature in a turbo-dynamo, three-bush bearing. The results are given in the following table.

	Test No. 1	Test No. 2
Clearance Space Between Bushes		
Journal and 1st bush	.0004 inches	.002 inches
1st bush and 2nd bush	.004 "	.004 "
2nd bush and 3rd bush	.002 "	.004 "
3rd bush and fixed bearing	.002 "	.004 "
Temperature of surrounding air	72° Fahr.	86° Fahr.
Amount of Oil Flowing through Bearing per minute	2.8 pts	10.56 pts
Temperature of Oil Entering Bearing	140° Fahr.	118° Fahr.
Temperature of Oil Leaving Bearing	176° Fahr.	140° Fahr.
Temperature of Bearing	234° Fahr.	167° Fahr.

In the above test the total load on the bearing was 8800 pounds and the angular velocity equal to 3000 revolutions per minute. It will be noticed that the temperature of the bearing with the lesser clearance was much higher than in the other bearing notwithstanding the fact that the temperature of the surrounding air was higher thus retarding to some extent the radiation of heat.

Formula for Coefficient of Friction.

The coefficient of friction for lubricated surfaces at constant temperature and oil film of uniform thickness is

$$\mu = \frac{k\pi v}{yp} = \frac{cv}{p} \quad \text{- - - - - - - - - - - - - - -(14)}$$

From results obtained experimentally by Stribeck and plotted in Figure 3 the value of the coefficient is given by the equation -

$$\mu = \frac{c\sqrt{v}}{p} \quad \text{- - - - - - - - - - - - - - - - - -(15)}$$

The experiments of Tower, reported in the Proceedings of the

Institute of Civil Engineers, in 1884 also verify this equation.

A more general expression for the coefficient of friction may be obtained by taking the following equation -

$$\mu = \frac{ck}{y} \times \frac{v^n}{p} \text{ - - - - - - - - - - - - - - -(16)}$$

in which the meaning of the symbols is as follows:

μ = coefficient of friction

c = constant

v = speed in feet per minute

y = thickness of oil film

p = pressure in pounds per square inch

n varies from 0 to 1/2

Instead of varying n for the different conditions, we may make the variations in k. For as the speed increases the temperature increases thus reducing the coefficient of viscosity. Also the law of shearing resistance is $k\frac{v}{y}$ whether at low or at high temperatures.

Osborn Reynolds has shown that $k = .000047e^{.0221t}$ in which t = temperature in degrees Fahrenheit. The solution of this equation is not readily made. Instead the following equation proposed by Dr. J. T. Nicholson may be used.

$$k = \frac{B}{t - 60°} = \frac{B}{\theta} = \frac{1}{500\,\theta} \text{ - - - - - - - - -(17)}$$

where $B = \frac{1}{500}$

θ = Degree of temperature above 60° Fahr.

t = 60° Fahr.

Dr. Nicholson says that this formula is sufficiently exact for temperatures occurring in ordinary practice. The formula ought to be verified experimentally, before it is generally

used.

Substituting in formula (16), the value of k obtained from (17) and taking n = constant = 1/2 we have

$$\mu = \frac{ck}{y} \cdot \frac{v^{1/2}}{p} = \frac{c\sqrt{v}}{500\,\theta\, p}$$

$$= \frac{900\sqrt{v}}{500\,\theta p} = \frac{1.8\sqrt{v}}{\theta\, p} \text{ - - - - - - - - - - - - } (18)$$

Equation (18) may be written

$$\mu\, p = \frac{1.8\sqrt{v}}{\theta} = M \text{ - - - - - - - - - - - - - - } (19)$$

which gives us the frictional resistances per square inch of projected area.

It will be shown later that the temperature of a bearing for steady running is given by the following equation

$$\theta_f = .66\, v^{3/4} \text{ - - - - - - - - - - - - - - } (20)$$

when heat radiated is equal to that generated by friction.

Referring to equation (19) let us consider the result of lengthening the bearing to twice its original length. The bearing pressure per square inch would be reduced one-half. But the value of M which varies inversely as the temperature and directly as the square root of the velocity only, would remain unchanged. The heat generated, therefore, has doubled so also has the surface for emitting heat. Hence, the journal will remain in the same condition regarding temperature as before. The work lost will be twice as much as before the journal was lengthened. Apparently, therefore, no advantage is gained from lengthening the journal. This has not been verified experimentally. (See American Machinist, December 28, 1905).

It may be stated, however, that an increased length

of journal reduces the liability to rupture of the oil film.

The Design of a Bearing.

The design of a bearing consists in finding its diameter and length for any given load, speed and method of lubrication in order that the bearing may run cool and that the requirements of strength and stiffness may be satisfied. Only that part of the design referring to the temperature conditions will be considered.

When a journal begins to rotate certain passive resistances are encountered, the overcoming of which generates heat. Chief among these resistances is friction and the heat generated due to this source is $\frac{\mu P \pi d N}{12J}$ B. Th. U. per minute

where P = load on journal

μ = coefficient of friction

N = revolutions per minute of journal

J = Joule's Equivalent

As the bearing warms up heat will be thrown off by radiation, the amount of which will depend upon the difference in temperature between bearing and ambient air, and the projected area of thebearing. Hence, if e be a coefficient of radiation, we shall have for the heat radiated

$$edl\theta = \frac{\mu P \pi d N}{12J} \quad \text{- - - - - - - - - - - - - -(21)}$$

Solving this equation for θ and eliminating μ by means of the relation expressed in (19) above we have, after reducing

$$\theta = \frac{(d\ N)^{3/4}}{3400\ e} \quad \text{- - - - - - - - - - - - - - - - (22)}$$

In these equations, θ represents the difference in temperature between that of bearing and 60° Fahrenheit.

The value of e, obtained from Stribeck's experiments is $\frac{1}{220}$ B. Th. U. This value of e should be further verified experimentally. Introducing this value of e in equation (22) and reducing, we have in round numbers

$$\theta = \frac{(d\ N)^{3/4}}{4} \text{ - - - - - - - - - - - - - - - -(23)}$$

The temperature, therefore, varies as the 3/4 power of the revolutions per minute; or for a given speed the temperature will vary as the 3/4 power of the diameter. The journal length does not appear in this equation; hence, lower temperatures for steady running may not be obtained by lengthening the journal. Increasing the length of the journal does decrease the unit pressure but the coefficient of friction varies inversely with the unit pressure, also the heat generated increases as the area for radiating it, hence frictional resistance and heat generated increase in the same ratio.

If the final temperature reached by the bearing be above a certain value, or the unit pressure be such as to force the lubricant from the bearing, the oil film will be destroyed. Also, at slower speeds, the eccentricity of the journal increases, and unless unit pressure is reduced contact between journal and bearing will occur.

A certain minimum speed, therefore, corresponds to every unit pressure below which perfect film lubrication can not exist. Sommerfield has shown mathematically that this speed is given by the following equation

$$V_o = K\frac{\delta^2}{r^2} \cdot \frac{p}{k} \text{ - - - - - - - - - - - - - - -(24)}$$

where v_o = minimum or critical speed at which oil film breaks down

δ = clearance between journal and bearing

r = radius of journal

k = coefficient of viscosity

K = a constant

A value for k between the ordinary limits of temperatures occurring in practice has been assumed. Substituting this value from (17) in (24) we have

$$v_o = K\frac{\delta^2}{r^2} \cdot \frac{p\theta}{c} = \frac{K}{c} \cdot \frac{\delta^2}{r^2}p\,\theta = Cp\theta \text{ - - - - - - - - } (25)$$

Here C represents the constant, $\frac{K}{c} \cdot \frac{\delta^2}{r^2}$ and its value varies as the square of the ratio of the clearance space to the journal radius. Its value for speeds not exceeding ten feet per second may be taken as $\frac{1}{40}$. This constant should also be verified experimentally. Equation (25), therefore, becomes

$$v_o = \frac{p\theta}{40} \text{ or}$$

$$\theta = \frac{40\ v_o}{p} \text{ - - - - - - - - - - - - - - - - - } (26)$$

This equation gives the rise in temperature above 60° F. in a bearing, for the given conditions of speed and unit pressure, to which a bearing may attain before there is danger of the oil film breaking down. Evidently, for an increase in temperature, the force of friction may follow the law as given for greasy surfaces in contact. Any condition of speed or pressure that tends to cause direct contact between journal and bearing should be avoided in design.

In the design of bearings proceed as follows: Calculate the rise in temperature due to the given speed by the formula

$$\theta = \frac{(d\ N)^{3/4}}{4} \text{ - - - - - - - - - - - - - - - - } (27)$$

Equate this value of θ to the value of θ in (26) thus

$$\frac{(d\ N)^{3/4}}{4} = \frac{40\ v_o}{p} \qquad (28)$$

But $v_o = \frac{dN}{12}$ and $p = \frac{P}{ld}$, hence substituting these values in (28) and solving for l we have

$$l = \frac{P}{40 d^{5/4} N^{1/4}} \qquad (29)$$

Formula (29) is the formula proposed for the design of bearings for rubbing speeds not exceeding 10 feet per second. It may be put in this form

$$\frac{ld}{P} = \frac{1}{40(dN)^{1/4}} = p \qquad (30)$$

The values of d and N occurring ordinarily in practice have been calculated and are shown in Figure 8.

As an illustration of the use of this formula consider the following problem. P = 3000#, N = 125. From Figure 8 for d = 2", p = 160 and $l = \frac{P}{pd} = \frac{3000}{160 \times 2} = 9.4"$ or for d = 3", p = 175 and $l = \frac{3000}{175 \times 3} = 5.7"$.

Factor of Safety

The pressures given in Figure 8 are called critical pressures, since they are those pressures which ought not to be exceeded if the oil film is to be preserved. We, arbitrarily, call the ratio of the critical pressure, obtained from Figure 8, to the actual pressure existing in the bearing the Factor of Safety. Expressed as an equation

$$\text{Factor of Safety} = n = \frac{p_c}{p} = \frac{\text{Critical Pressure}}{\text{Actual Pressure}}$$

The value of n depends upon the change in diameter and length of journal, A change in the length produces a change only in the actual bearing value, while a change in the diameter produces a change not only in the actual bearing value but also

in the critical pressure. Thus when l varies alone the factor of safety is

$$n_1 = \frac{pc_1}{P \div l_2 d_1} = \frac{pc_1}{p_1} = \frac{40 d_1^{\frac{5}{4}} N^{\frac{1}{4}} l_2}{P p_1} \quad \text{(See Eq. 30)}$$

and when d varies alone

$$n_2 = \frac{pc_2}{P \div l_1 d_2} = \frac{40 d_2^{\frac{5}{4}} N^{\frac{1}{4}} l_1}{P p_1}$$

These principles may be illustrated by a numerical problem. Thus let $d_1 = 4''$, $N = 50$, $l_1 = 5''$, $p_1 = pc = 150\#$ (From Figure 8). Then $P = 3000\#$. Let l_1 increase to $l_2 = 6''$. Under this condition the critical pressure remains constant and the factor of safety, $n = \frac{pc}{p_2} = \frac{150}{3000 \div 6 \times 4} = \frac{6}{5} = 1.2$. An increase, therefore, of 20% in the length of the journal, enables it to take 20% more load before failure of the oil film may occur.

If now we change the diameter from d_1 to d_2, keeping the original length l, we have $n_2 = \frac{pc_2}{p_2} = \frac{40 d_2^{\frac{5}{4}} N^{\frac{1}{4}} l_1}{P\ p}$.
In order to have the factor of safety the same in each case we must have $n_1 = n_2$ or $\frac{40 d_1^{\frac{5}{4}} N^{\frac{1}{4}} l_2}{P\ p_1} = \frac{40 d_2^{\frac{5}{4}} N^{\frac{1}{4}} l_1}{P\ p_1}$

Simplyfying $\left(\frac{d_2}{d_1}\right)^{\frac{5}{4}} = \frac{l_2}{l_1}$ or

$$d_2^{\frac{5}{4}} = \frac{d_1^{\frac{5}{4}} l_2}{l_1} = \frac{4^{\frac{5}{4}} \times 6}{5} = 6.79'' \text{ and}$$

$$d_2 = 4.6''$$

Hence increasing the diameter of the journal from 4" to 4.6" gives the same factor of safety as is obtained by increasing the length from 5" to 6".

PART II

BEARING METALS.

The Microstructure of Bearing Metals.

Within the past few years, the application of the microscope to the examination of metals has developed very rapidly. Accurate methods of work are now known and a vast amount of data has been collected. Microscopic examination can supplement chemical analysis. It does not enable us to determine what chemical elements are present but it does enable us to make out the structure of the alloy, and particularly the part or parts of the alloy that may have separated as the alloy cooled. The properties of alloys depend to such a large extent on their structure that without a knowledge of this structure the various properties can not be understood. Many of the failures in the making of alloys are brought about by small changes in the method of treatment, or in other ways, and failures can not be prevented till the cause which produces them is known. The microscope may, therefore, be used to determine some of the facts which chemical analysis does not reveal.

For the microscopic examination of metals three things must be taken into account: the microscope; the preparation of the sample; and the methods of examination.

The Microscope. - The microscope is the most important part of the outfit. Good work may be done with an ordinary instrument but one specially made for metallographic work is much better.

In ordinary microscopic work the objects viewed are transparent and are, therefore, seen by means of light

reflected from below. Metals, however, are opaque no matter how thinly the sample may be finished. Hence, all such objects must be examined by light reflected from above. This calls for an instrument somewhat differently constructed from the ordinary biological microscope.

The Preparation of the Sample. - In preparing the sample for examination under the microscope, the first thing to be done is to obtain a smooth surface, free from scratches. This finished surface is obtained by a series of polishings, a finer polishing material being used at each stage than the one before. This, step by step, polishing is important because of the abraiding powder of the material used. The work may be polished by hand or by machine. Several machines either hand or power driven are obtainable for this purpose. When the polishing is complete, the surface will appear smooth and bright and will show no structure to the naked eye.

In order to reveal the structure, the surface must be treated with some reagent which will attack the surface. The different constituents will be attacked at different rates so that some portions will stand out in relief, while other parts upon which the action has been greater will be entirely removed. This relief, however, is so slight that both portions will be in focus under the microscope at the same time.

Methods of Examination. - The fractured surface of a metal is so irregular that it is impossible to get it into focus. Also the cause of the fracture depends upon so many conditions that an examination of the mere fracture gives but little, if any, information about it. To permit of focusing

the sample should show a perfectly plane surface, which, as already stated, is obtained by polishing.

In reporting the results of an examination a photograph should always be included. The magnification should also be given, thus: x 40, meaning that the photograph is 40 times larger than the sample. Also, the illumination should be given thus: ob for oblique illumination and vl for vertical illumination. This is necessary because the appearance of the object varies with the character of the illumination. A surface appearing bright with an oblique illumination often appears dull by vertical illumination. Again, if the surface be dull, the oblique ray will not be regularly reflected, but will be scattered so that nearly all of the reflected light will enter the object glass and the surface of the sample will appear bright. Also, if the light be sent down vertically upon the surface only a small part will be reflected and the object will, therefore, appear dull or dark.

Good judgment and experience are required for the correct interpretation of the meaning of the structure as displayed under the microscope.

It is not possible in this connection to show any photograph of microscopic work. Facilities for such work were not available. Further, the author, on account of inexperience with this kind of work, does not consider himself capable of discussing with any degree of completness such work were it available. For further information, therefore, the reader is referred to two very excellent articles treating on

this subject, the one by Professor Melvin Price in Vol. XXVI of the Transactions of the American Society of Mechanical Engineers, and the other by, Mr. G. H. Clamer in Vol. 133 of the Journal Franklin Institute. Further references pertaining to this subject are also given in last part of this thesis.

Points to be Considered in Selecting Bearing Metals.

In selecting an alloy or a metal to be used as a bearing - journal support - the most important point to consider is that of wear. If perfect film lubrication could be constantly maintained any substance, in general, would answer equally as well for a bearing metal. Such a condition of lubrication is impossible of attainment owing to the various conditions of service to which bearings and journals are subjected. It is, perhaps, true that a journal and bearing may be designed in such a manner as to give perfect film lubrication. This requires, however, that the speed be not below a certain critical value; also, that the unit pressure be not excessive. Evidently, when the parts are in contact wear occurs and the friction is increased. It is mainly because of these two latter conditions that careful consideration should be given to the selecting of bearing metals.

Bearing metals may be formed of a hard, strong material such as phosphor-bronze or they may consist of a main frame of a hard or strong material with a bed of softer metal cast in to form the actual working surface. An illustration of the latter type of bearing metal is the glyco patented bearing which consists of a skeleton frame work of steel to

support the softer glyco bearing metal. Usually, however, the various metals forming the alloy are cast into one mass, the crystals of the harder metals of the alloy forming the main support for the journal, while the softer parts give plasticity and anti-friction qualities to the bearing. In some cases the bearing is lined with a softer metal so that the journal may easily adjust or seat itself in the bearing. Lead was at first used for this purpose but gradually alloys of various kinds have come into general use. These alloys are of two general classes: the one class including those alloys in which the chemism of all the elements involved is perfectly satisfied while the second class include those alloys in which the various constituents form a mechanical mixture rather than a chemical compound. In the alloys whose various parts are chemically united the grain is close, fine and uniform. Such alloys possess the greatest molecular tension, a property which enables them to offer great resistance to crushing, to tensile strength and to heating. The mechanically mixed bearings may include some or all of the various constituents partly combined chemically, but because of improper proportions certain constituents may be only mixed, or mechanically united, Such bearings are coarse and of uneven grain, with anti-friction qualities less developed than in the chemically united alloy.

The physical properties of an alloy which determine its value as a bearing for journals are: (1) Resistance to crushing, (2) Elastic tension, (3) Tensile strength, (4) Re-

sistance to heating, and (5) Anti-friction.

Resistance to Crushing. - A test of the crushing strength of an alloy used as a bearing metal is of extreme importance since the alloy must be hard enough to support the load without deformation. If too brittle the bearing will crack under the load. This failure is due to lack of compressive strength, perhaps, more than lack of crushing strength, but as the nature of the stresses in either case are similar, a division of the former is not made. The temperature also has a marked effect upon the crushing strength of a bearing metal; the resistance to crushing decreasing rapidly as the temperature increases.

The value of the crushing resistance should not be too low. Thus when first put into service, unless great care has been exercised in fitting, the area of contact between journal and bearing is small, the result is a very high unit pressure. However, after running a short time the bearing soon wears, and thus the pressure is reduced to that for which it was designed. Also in machines transmitting a varying or intermittent force, the crushing resistance must be high to avoid having the bearing metal alloy forced or squeezed out of the bearing.

Elastic Tension. - By the elastic tension of a metal is meant the force required to spring the metal to a position from which it will not return to its original position when the force is removed. Its value is usually expressed in pounds per square inch, and its leverage is usually taken as one inch. Elastic tension is one of the most necessary and

important properties in a good bearing metal. It is a measure of the metals ability to withstand the vibration, jarring and pounding met with in service, without being forced out of the boxes. This is a condition existing to a greater or less extent in all classes of bearings. Particularly, in railroad and electric traction service is this property of the utmost importance.

Tensile Strength. - The wearing quality of a bearing metal is in direct proportion to its tensile strength for the greater the molecular tension of a metal the more force is required to separate its molecules. By wear is meant the tearing off of small particles from the worn body. It is evident, therefore, that if the particle of metal torn away is twice as large in one case as in the other, the wear will be twice as rapid. It is here assumed that the coarser grained metals have the larger sized particles torn out, that is, have the more rapid wear. This fact has been thoroughly proven experimentally. In the instance of case-hardened steel the wear is less rapid than in the untreated metal. The granular structure of a piece of case-hardened steel is very fine as shown by the fracture. Experimentally, it has been found that alloys which exhibit the greatest tensile strength show the least wear with increased service. Also, Mr. Dudley states that in experiments made by him on car journals with phosphor-bronze bearing metal the bearing lost about one pound per 25,000 miles of travel while the journal composed of a meterial higher in tensile strength lost only about

one-third of a pound for the same distance travelled.

Resistance to Heating. - By this expression is meant the amount of heat required to overcome molecular tension. One manufacturer states that any metal which requires 520° Fahr. to overcome its molecular tension will give safe and satisfactory service under pressure of 100 pounds per square inch and a temperature approximately of 350° Fahr. These results ought not to be depended upon until proven experimentally. In general, it may be said the harder the bearing metal is the more readily will it heat. Expressed otherwise, the softer the alloy the less liability there is for the bearing "to heat" in actual service.

The resistance to crushing, elastic tension and tensile strength of all metals decrease as their temperature increases. A metals resistance to heat is of great importance when considered in conjunction with its other physical properties and the condition under which it is to be used.

Anti-Friction. - The question of friction is very largely a question of the method of lubrication and the kind of lubricant used. If the bearings are well lubricated, the journal and bearing are not in contact with each other but only with the oil film, and, therefore, the friction is independent of the kind of materials used.

It is always desirable to select a bearing metal which gives a low coefficient of friction, since it is always best to place every possible factor on the right side of the problem of service; but of all the physical proper-

ties of metals considered, the anti-frictionquality is of the least importance.

The anti-friction property of a bearing metal is measured in degrees and represents the greatest degree of angle, as measured from the top of the circle at which a cube of the metal will slide down the incline plane, when its polished surface (unlubricated) is resting upon the polished surface of a steel plate.

Relation Between Composition and Wear.

This relation is not of special importance and might very properly be omitted. It has been stated by many experimenters as a result of their investigation that when a journal is well adjusted the friction is practically the same regardless of the composition of the metals in contact, and depends exclusively upon the lubricant because the parts are not in reality in contact only with the film of oil. The friction, therefore, partakes more of the nature of fluid friction. If it were possible to keep the bearings accurately adjusted and perfectly lubricated, it would be of little importance what metal is used for bearings. This, however, is in general, impossible and the nature of the bearing metal may, therefore, become an important factor in preventing such accidents as hot boxes or burning out of bearings.

The question of friction has already been discussed in the first part of this thesis. One or two points may, however, be very briefly reviewed. The early experimenters

found that the coefficient of friction between two bodies when relative motion was just beginning was a constant and that as the pressure between the two bodies was increased up to a certain load, the friction increased nearly proportional to the pressure. Above a certain load the coefficient of friction increases rapidly, the surfaces heat, and finally cut into each other, at which point occurs an abrupt and very great increase in the coefficient of friction. The load at which cutting or "seizing" occurs is greater the harder the metals in contact. Also the coefficient of friction is smaller the harder the metal. It would appear, therefore, that to reduce friction as well as to avoid seizing hard substances such as phosphor-bronze should be used for bearing metals.

The use of hard substances for bearings has one serious objection. Unless very great care is taken in fitting, the load is not uniformly distributed but is concentrated at certain points. This gives rise to excessive loading or pressure on these points and soon leads to heating and abrasion. The defect may, however, be overcome if the material forming the bearing has a certain amount of plasticity so that it may mould itself round the shaft thus increasing the contact area.

Two apparently contradictory characteristics, namely, hardness and plasticity ought to be found in a bearing alloy. This result is obtained by using metals composed of hard grains imbedded in a plastic matrix. This is the prin-

ciple sought in all anti-friction alloys. The compression test determines the plasticity and also shows whether or not the metal is brittle. The composition of the alloy is, therefore, of considerable importance, because structure is dependent on composition. Alteration in structure may occur if the alloy is unduly heated in service, but usually such changes are small. However, the bearing metal alloy may suffer a radical change due to unduly heating in the foundry or in preparation for casting. Such defects may be segregation, coarse crystalline structure, oxidation products, and enclosed gases. Segregation usually results when excessive heat has been introduced, especially when the proportions of the constituents in the alloy are not properly added. This is particularly true with the copper-tin-lead alloys. An excess of lead separates and mixing mechanically with some of the copper forms dark spots, producing regions of high heating capacity. Segregation may be partly prevented by rapid cooling under which condition, however, the metal may be less ductile. Coarse, crystalline structure is due to a very high temperature of the metal when moulding, or also to the presence of impurities, such as silicon, antimony or phosphorus. The introduction of silicon and phosphorus if in small quantities form deoxidisers, close up the grain and increase the strength, but if in excess they cause certain compounds to be enclosed and give rise to a coarse, crystalline structure with a consequent loss of ductility and durability. Enclosed gases and oxidation products give rise to a very serious

weakness in bearing alloys. Any of these conditions cause a bearing to become unduly heated. They may be very largely eliminated by sufficient knowledge and care on the part of the moulder.

The important points, therefore, to be considered in selecting a bearing metal are; wear, crushing and tensile strength, composition and structure, resistance to heating and friction. Perhaps the item of cost should also be added. Evidently no one alloy can successfully meet all of these requirements for the metal showing the smallest rate of wear may have the greatest coefficient of friction. The items given above, therefore, must be studied in detail and the peculiar qualifications of each balanced against the others according to the special features required.

Alloys Suitable for Journal Bearings.

The principal metals used in the manufacture of alloys for bearings are; copper, tin, lead, zinc, iron, antimony and aluminum. In additon, either as essential or accidental constituents, the following are included: phosphorus, manganese, silicon, bismuth, mercury, nickel, sulphur, arsenic, and cadmium. The various alloys of these metals used for bearings may be conveniently grouped as follows: white metal alloys; copper and tin alloys; copper, tin and lead alloys; phosphor-bronze; miscellaneous alloys.

The different combinations of the above metals in alloys are already numerous and the possibility of further combinations is very great. It is the business of the metallurgist to discover the various combinations of the above met-

als forming alloys; and the business of the testing engineer to find out which of these alloys may be successfully used as journal bearings. Discoveries and experimenting along these lines have been carried on for at least 25 years, but as yet no alloy has been found which gives perfect success in service. New combinations of metals and various processes in treatment of alloys are continually appearing, some possessing much merit, others of no consequence. In general, improvements are being made and perhaps at no great distant day some one will discover the proper combination of metals which with the proper heat treatment will produce an alloy giving absolutely perfect success in service as a bearing metal alloy.

Composition and Structure of Alloys used as Bearing Metals.

The information given here has been obtained principally from the researches of Charpy (Bulletin Soc. d'Encour. l'indus Nationale, 1898). A brief account and the results of these researches were given by Mr. A. H. Hiorns in The Mechanical Engineer, Vol. XXII, p. 799. It is from this article by Mr. Hiorns that the following is taken.

Lead-Antimony.

These metals alloy in all proportions and the alloy becomes harder and more brittle as the antimony increases. The only proportion free from segregation is the eutectic with 13 per cent antimony. When the proportion of antimony is less than 13 per cent crystals of lead and eutectic appear; with more than 13 per cent antimony, crystals of antimony and lead appear.

It has already been stated that an anti-friction alloy should consist of hard grains which carry the load and are embedded in a plastic matrix so that the bearing may readily adjust itself to the shape and irregularities of the shaft. Such a condition is met with in this alloy containing more than 13 per cent antimony, however, the alloys with 15 to 25 per cent antimony are the most suitable. With 13 per cent antimony the friction is greatly increased but the wear very much diminished. Of course, this is a great advantage where unit pressures are low.

Lead is the best wear-resisting metal known, but upon increasing the antimony the wear increases due to the splitting up of the hard particles, the friction, however, is reduced and the temperature of running is diminished.

The compressive strength of the alloy increases rapidly on addition of antimony to the lead up to about 15 per cent. Beyond this up to 30 percent antimony, there is little change in the compressive strength but above 30 per cent antimony the compressive strength rapidly increases. Above 30 per cent the crystals of antimony become more united and form a more continuous net work, they then bear a portion of the load and the strength increases. But the crystals of antimony have no plasticity and break when the load reaches a certain limit and the alloy is reduced to fragments. Hence, arises the necessity of having great strength and plasticity in the matrix. This is better done with ternary than with binary alloys.

Lead - Tin - Bismuth.

There are no chemical reactions in this alloy, hence the three constituents may occur in any per cent. Alloys of these metals may be divided into three groups according to which metal is deposited first. With 21 per cent lead, 5 per cent tin, and 74 per cent bismuth polished and slightly etched and put under the microscope the bismuth appears white which solidifies at about 350° Fahr. Surrounding the crystals of bismuth are areas of bismuth and tin eutectic. The matrix is a ternary alloy appearing black under the microscope and whose complex nature is only revealed by higher magnifying powers. This alloy is apparently hard and brittle and possesses but little plasticity.

Tin - Antimony - Copper.

The common name for this ternary alloy is Babbitt metal. Tin-antimony alloys with 10 to 40 per cent antimony, and after freezing, gives cubes of the compound antimony-tin. These cubes are less hard and brittle than pure antimony. Alloys of copper and tin containing 5 to 50 per cent copper are composed of hard crystals of the compound $SnCu_3$, imbedded in an eutectic of tin and $SnCu_3$. The latter crystallises in needles with a tendency to form six pointed stars.

In this alloy with an excess of tin crystals of tin are found and these have not the requisite properties for bearings, since the grains would be soft, embedded in the eutectic. Such bearings possess little compressive strength and would, therefore, be easily distorted under small loads.

Charpy found the alloy with 83 per cent tin, 11-1/2 per cent copper and 5-1/2 per cent antimony to possess the greatest compressive strength. Probably the best alloys should be within 3 or 4 per cent of this composition.

The alloy (Babbitt metal) is easily made by melting copper first under a layer of charcoal, then adding a part of the tin and stirring with a charred stick. The antimony is next added, and finally the remainder of the tin. The whole should be vigorously stirred. When the temperature has been lowered to about 932° Fahr. the alloy is cast into the mold which should be previously warmed to about 200° Fahr.

Lead - Tin - Antimony.

Lead and antimony do not readily combine, and when the antimony exceeds 13 per cent, hard grains of antimony appear. Lead and tin alloys do not contain any definite compounds, they are composed of crystalline needles of lead or tin, according to the composition, embedded in eutectic alloy of 38 per cent lead and 62 per cent tin. Both lead and tin being soft, the properties of lead-tin- alloys vary little with composition. The compressive strength increases by addition of either metal (tin or lead) and is greatly raised by adding antimony. The addition of lead causes the least increase in compressive strength. To avoid brittleness the antimony should not exceed 18 per cent.

Microscopic examination shows hard grains of antimony-tin in antimony, in all alloys containing over 10 per cent antimony embedded in eutectic. The tin intervenes as

a constituent of the hard grains, diminishing their hardness and also their brittleness. Tin is also in the eutectic, increasing its compressive strength.

Alloys of tin, lead and antimony are therefore, superior to binary alloys of lead and antimony, as anti-friction alloys. The proportion of tin must be between 10 and 20 per cent and of antimony between 10 and 16 per cent. An alloy with 80 per cent lead, 12 per cent tin, 8 per cent antimony has been used successfully as a metallic packing for piston rods by certain European railways. Also one alloy with 70 per cent lead, 10 per cent tin, 20 per cent antimony is used for packing for eccentric collars.

Lead - Copper - Antimony.

Lead and copper alloy only in small proportions and when large quantities of the metals are melted together, they separate on cooling each containing a little of the other. But copper and antimony alloy in all proportions forming at least one compound which crystallizes in the form of needles of a violet color. This compound occurs also in the eutectic and increases its resistance to compression. The addition of too much copper produces segregation the same as copper and lead if used alone. An alloy of 65 per cent lead, 25 per cent antimony and 10 per cent copper is used for packing.

Zinc - Tin - Antimony.

Zinc and tin do not readily combine, hence, crystals of tin or zinc are found embedded in eutectic containing about 10 per cent tin. Alloys of zinc and antimony form a defin-

ite compound which is hard and produces an eutectic with 3 per cent zinc. If we consider only these alloys in which zinc predominates they are probably formed of zinc, tin or antimonide of zinc. No ternary compound is formed, hence, these alloys may be divided into three groups according as the zinc, tin or antimonide of zinc crystallizes first. Only those alloys of the last group possess suitable anti-friction properties. With an excess of zinc, the alloys possess a high compressive strength, and tin diminishes the brittleness. Alloys of zinc become brittle when heated and are, therefore, not suitable for bearings. They are used only when first cost is the dominant factor.

Copper - Tin - Lead.

An alloy of these constituents form what is generally called bronze. There are two divisions; (1) copper and tin with small quantities of other elements such as phosphorus, zinc, etc.; and, (2) copper, tin and lead. The latter is the more frequently used. The copper-tin alloys possess greater compressive strength than the white metals. (Tin-antimony-copper) and the compressive strength increases with the proportion of tin. Phosphorus has no influence on the compressive strength.

Alloys of copper-tin up to 20 per cent of tin do not vary in structure. Phosphorus, if present, is localized in the eutectic, modifying its hardness. The eutectic is much stronger than pure copper and it is this which regulates the strength of the mass. The addition of lead increases its plasticity.

The copper-lead-tin alloy is now the chief of our standard bearing bronzes. The addition of the lead to the copper-tin produces less liability to heating with the same lubrication and also diminished the rate of wear. The following table is by Dudley, of the Pennsylvania Railroad Company:-

C O M P O S I T I O N

METALS TESTED	Copper	Tin	Lead	Phosphorus	Arsenic	Relative Wear
Phosphor-bronze, Standard	79.60	10.00	9.60	.80	---	1.00
Ordinary bronze	87.50	12.50	----	---	---	1.49
Arsenic bronze "A"	89.20	10.00	----	---	.80	1.32
" " "B"	82.20	10.00	7.00	---	.80	1.15
" " "C"	79.70	10.00	9.50	---	.80	1.01
Bronze "K" (1)	77.00	10.50	12.50	---	---	.92
" "K" (2)	77.00	8.00	15.00	---	---	.86

Dudley's conclusions were: (1) Phosphorus and arsenic exercise no marked influence on wear, and are useful only for sound castings; (2) The metal which wears out the least is the one capable of undergoing the greatest distortion before breaking; (3) The rate of wear decreases with increase of load.

Clamer of the Ajax Metal Company, in 1903, gave the following table as the results of tests made with different alloys:-

Copper and Tin, and Copper, Tin and Lead Series.

	Copper	Tin	Lead	Friction	Temperature above Room	Wear in grains
1	85.76	14.90	----	13	50	.2800
2	90.67	9.45	----	13	51	.1768
3	95.01	4.95	----	16	52	.0776
4	90.82	4.62	4.82	14	53	.0542
5	85.12	4.64	10.64	16-1/2	56	.0380
6	81.27	5.17	14.14	18-1/2	58	.0327
7	75.00?	5.00?	20.00?	18-1/2	58	.0277
8	68.71	5.24	26.67	18	58	.0204
9	64.34	4.70	31.22	18	64	.0130

The conditions in all the above tests were as follows:-

Total number of revolutions made- -100,000

Revolutions per minute- - - - - - - 500

Size of journal- 3-3/4" diam., 3-1/2" long

Pressure per square inch in lbs.- - 1,000

Lubrication- Galena & Coach oil fed by Cotton Waste

For general purposes Clamer adopted the following alloy as the best: Copper 64, tin 5, lead 30 and nickel 1 per cent. What is true of alloys with less than 15 per cent of lead, as examined by Dudley, is also true of high-lead content alloys, namely, that the rate of wear diminishes with increase of lead, or what is the same thing, the rate of wear diminishes with the diminishing compressive strength or increased plasticity of the alloy.

Bronzes containing zinc may be cheap but zinc increases the rate of wear and has a tendency to segregate lead. Take the following:-

Copper	Tin	Lead	Zinc	Temperature above room	Wear in Grains
85.0	4.5	10.5	---	56	.0380
82.3	5.3	10.3	2.0	68	.0415
80.0	4.5	10.0	5.5	66	.0466
77.5	5.5	10.5	6.5	68	.0472
74.5	4.5	10.5	10.5	69	.0846

Total number of revolutions made - - - 100,000

Revolutions per minute - - - - - - - - 525

Pressure per square inch in pounds - - 1,000

The composition of the bronzes is the reverse of that of the white alloys. Instead of hard grains in a plastic eutectic as in white metal, we have soft grains in a hard eutectic for the same degree of plasticity in the bronzes. Bronze has a greater tendency to wear the shaft than has white metal.

As the unit pressure increases the oil is gradually driven out from the space between the shaft and bearing. Under these conditions the wear of the white metal would be excessive and if the lead continued to increase the metal would fuse. In the case of bronze more heat would be required but the friction would be greater when fusion did occur, since some of the copper would adhere to the shaft thus forming a rough surface.

As bearing metals bronzes are inferior to white metals since they are less plastic and do not readily mould themselves as well around the axle. Their greater strength does not permit a heavier load for their lubrication is interfered with and heat is, therefore, generated rapidly. As already stated, bronzes, on account of their constitution, have a greater tendency to cut the shaft than the white metal alloys.

CONCLUSION.

An anti-friction alloy should have hard grains in a plastic matrix then the load is carried by the hard grains which have a low coefficient of friction. Cutting, therefore, takes place with difficulty. The plasticity of the cement makes it possible for the bearing to adjust itself round the shaft thus avoiding local pressures. These properties may be obtained in binary alloys with such metals as antimony, tin and copper which form chemical compounds. The requisite properties are better obtained in ternary alloys which give a good plastic matrix (eutectic). To test an anti-friction alloy compression and the microscope are valuable aids.

Testing of Bearing Metals.

There is probably no other material used in the construction of machinery regarding which so much uncertainty exists as that of bearing metals. Tests almost innumerable have been made and with results almost as varied. The subject is, therefore, worthy of very careful consideration and experimentation.

Structure and composition of bearing metal alloys no doubt exert a marked influence on their successful operation in practical service. Segregation, hard spots, etc., are frequently the cause of much annoyance in practice. Further, the composition may be such that the bearing readily adapts itself to any irregularity existing in the shaft thus preventing concentration of the load with its bad results.

The principal points to be considered in the testing of alloys are as follows:-

1. Wear on bearing
2. Wear on journal
3. Friction
4. Temperature of running
5. Compressive strength
6. Structure

The first four of these tests are made on machines designed especially for this kind of work. There are a great many machines in use for such purposes, but few, if any, are satisfactory. Results obtained in this manner are only comparative and can not be compared to the actual service test made under actual working conditions.

The wear tests are of considerable importance and by comparing with a given standard, give the ratio of resistance to abrasion. The conclusions arrived at in connection with alloys thus far tested are as follows:-

Wear. - (1) Decreases with the decrease of tin in a copper-tin alloy; (2) Decreases with decrease of tin in a cop-

per-tin-lead alloy; (3) Decreases with increase of lead in a copper-lead alloy or copper-tin-lead alloy; (4) Increases with increase of zinc in copper-tin-lead-zinc alloy; (5) Increases with increase of antimony in lead-antimony alloy.

Wear on Journal. - In general, wear increases with decreased compressive strength which means that under normal conditions hard metals in the journal cause less abrasion in bearings than soft metals.

Friction. - As previously stated, friction depends, theoretically only, on the kind and nature of the lubricant used, and is independent of the kind of metal composing the journal or the bearing. There are no theoretically perfect surfaces perfectly adjusted; hence, some consideration should be given to the material comprising the journal. In general, the softer the metals in contact the higher the coefficient of friction. When lubrication is interferred with or foreign matter becomes interposed between bearing surfaces, thus producing an abnormal pressure it is necessary that the alloy be soft and yielding in order to distribute the pressure. For this reason, softer metals should be used even though the coefficient of friction is higher with the softer compositions.

Compressive Strength. - A test of the compressive strength gives a general knowledge of the pressure under which the metal will operate successfully, whether the alloy is brittle and if it is sufficiently plastic to withstand a reasonable amount of abuse before heating.

Structure. - An examination of the general structure of

the alloy is quite important as it shows defects, such as segregation, coarse crystalline structure, dross or oxidation products, any of which could be reasonably supposed to increase friction. It is for this reason that the specifications of the large railroad companies call for an examination of the fracture of at least one brass in each one hundred.

It has also been stated that a successful bearing metal alloy should consist of at least two structural constituents, one hard part to sustain the load and one soft part to give plasticity. An investigation of the structure therefore, tells us whether or not an alloy is possessed of such an arrangement of its parts.

Bearing Metals for Automobile Work.

The automobile is a light-weight, high powered, generating plant. The necessity for reducing the weight of the various parts of the machine has given rise to improved methods of production in the foundry, and a careful analysis and testing of the metals there used. As a result (Considering only bearing metals) bearings have been made with greater strength and better wearing qualities by using different combinations of old alloys, and by adding new alloys. This allows bearing castings to be made of a thinner section which results in decreasing the weight.

In recent years there has come into use many patented and secret combinations of bearing metals as well as metals requiring other properties of strength in castings. Many of these patented combinations are old while the secret combinations can be analyzed by the foundry chemist in a few hours, and if of any value may be easily manufactured and used. Many of these patented alloys and alloys of secret combinations have failed to give satisfaction when given practical working tests. Some are, however, of value and are within the reach of every foundryman. The various constituents usually occurring with percentages are given in Table I. (See page 53).

Copper. - This is the most important constituent used in the various bearing metals excepting the white bearing or babbitt metals. Its two qualities which make it especially valuable as an ingredient in a bearing metal alloy are its

TABLE I *

Kind of Bearing	Copper	Lead	Tin	Phosphor-tin	Zinc	Antimony	Nickel	Cadmium
Friction	90.0	----	9.0	1.0	----	----	---	----
Friction	88.6	3.0	8.0	1.0	----	----	---	----
Medium Pressure Friction	78.0	12.0	8.0	1.0	1.0	----	---	----
High Pressure Friction	80.0	8.0	10.0	2.0	----	----	---	----
Locomotive	89.0	1.4	9.6	---	----	----	---	----
Pennsylvania Railroad	77.0	15.0	8.0	---	----	----	---	----
Tough	77.0	----	11.5	---	11.5	----	---	----
Engine	89.4	----	10.4	---	0.2	----	---	----
Heavy	84.2	----	13.2	---	2.6	----	---	----
Heavy	84.0	----	14.5	1.5	----	----	---	----
Heavy	82.0	4.0	12.5	1.5	----	----	---	----
Machinery	87.5	----	12.5	---	----	----	---	----
Hard Piston Ring	78.0	----	----	22.0	----	----	---	----
Nickel	65.0	29.0	----	5.0	----	----	1.0	----
Copper	92.0	----	----	8.0	----	----	---	----
U. S. Government Friction	3.7	----	88.8	---	----	7.5	---	----
Licensed Association Automobile Manufacturers No. 1	4.0	----	89.0	---	----	7.0	---	----
Ditto No. 2	-----	75.0	10.0	---	----	15.0	---	----
Siemans & Halske Berlin	----	----	----	---	47.5	5.0	---	47.5

* Aluminum may be used in most of these alloys in very small quantities. Not exceeding about 1 per cent.

ductility and heat-resisting powers. The addition of lead to copper softens the copper alloy and makes it more plastic. Thus, when the bearing becomes warm, the lead liquifies and the copper supports and resists the friction of the journal running in the shaft. Too much lead may cause the bearing to be forced out endwise and too little may not allow the copper to act properly. Lead is the best wear-resisting material known, it, therefore, tends to lengthen the life of the bearing. However, the lead increases the coefficient of friction. Lead will not combine with copper below a white heat unless the copper has been previously melted with tin. The more tin the more perfect will be the combination of the lead with the copper. The high temperature thus required necessitates a special furnace for the making of copper-lead alloys. Another function of the tin, if in proper proportions (see table) adds to the rigidity of the metal, hardens it without increasing its brittleness and produces an alloy very high in compressive strength. Examined under the microscope after polishing and etching, it shows hard, white crystals, cube-shaped, embedded in a soft matrix. Tin also tends to lessen the life of the bearing by increasing its rate of wear.

Phosphorus. - The function of phosphorus in the production of phosphor-bronze bearings is to make the metal more homogenous. Pin holes are likely to occur in copper and tin alloys. About 0.25 per cent phosphorus or 5 per cent phosphor-tin is the correct amount to use. If more is used, pin

holes in the metal will result. It might also be stated that phosphorus is generally used in the form of phosphor-tin as it is much less dangerous to the eyes to handle and also in this form mixes with the metal a great deal better. Phosphorus ought not be used in alloys containing zinc owing to its tendency to cause pin holes. Chemical analysis of phosphor bronze castings usually shows only a trace of phosphorus, the greater part of it having oxidized after doing its work.

Zinc. - Zinc on account of its cheapness is largely used in bearing metals in place of tin. It tends to reduce toughness and produce brittleness, both of which qualities are furnished by the addition of tin. If the zinc is in excess of 33 per cent of the mass by weight in an alloy with copper it produces a metal too brittle to be of value as a bearing. Its atomic weight and specific gravity is less than that of tin and experimentally it has been proven that metals of a lower atomic weight increase the force of friction. However, zinc in combination with tin and copper is extensively used in the manufacture of bearing metals.

Antimony. - Antimony when used with copper, phosphorus and tin tends to harden the alloy, produces brittleness and aids in the formation of a crystalline structure. It is also a very poor, wear-resisting material. It must, therefore, be used in small quantities not exceeding about 15 per cent. Perhaps the only claim for its use is that it assists in producing a certain degree of hardness. In the babbitt metals, however, antimony is used in quite large per-

centages. Mixed with lead it produces an alloy known as antimonial lead which is used a great deal on account of its cheapness.

Aluminum. - Aluminum when present in small amounts aids in the production of good smooth castings of the bronzes. A large part of the metal oxidizes on the surface of the casting and forms a smooth silky covering which prevents the volatilisation of the spelter. It does not wear well and being low in atomic weight increases the friction.

Nickel. - The Use of nickel is to reduce the temperature at which solidification of a few of the bronze metals occur. Cooling at a lower temperature prevents the squeezing out of any part of the lead that may not have combined with the cop per.

Cadmium. - This metal is added to an alloy produced and patented in Germany. The alloy contains from 45 to 50 per cent cadmium, 45 to 50 per cent zinc, and from 5 to 10 per cent antimony. This bearing is easier machined than white metal, fills the mould more completely in casting, has relatively great hardness, and a low coefficient of friction. Varying the percentages of cadmium and zinc from those given above increases the coefficient of friction and reduces the other good properties of the alloy as mentioned above.

Bismuth. - Bismuth when added to an alloy in small quantities gives to the alloy the property of expanding at the instant solidification occurs. This is especially desirable when metal moulds are used but of questionable beneficial re-

sults when sand molds are used. It should be added to the alloy just before pouring as it fuses easily and also causes other metals to fuse easily.

Mixing Metals.

In mixing bearing metals the various ingredients having the highest fusing point should be melted first, or in the order in which their fusing point descends. The surface of the molten metal should be well covered with powdered charcoal to a depth of at least 1/4 inch. Each metal as it is added should be well stirred in order to insure a perfect mixture. The alloy should not remain over the fire after all the parts are melted but should be poured at once into ingots and remelted when wanted for castings. In remelting a more perfect mixture is assured. Sometimes when four metals are used in the alloy and the fusing points are very different, the one containing the lowest fusing point is omitted and only the three run into the ingot. Upon remelting the ingot for castings the fourth metal is added together with about 0.25 per cent of bismuth by weight. The bismuth should not be added until the crucible has been removed from the furnace.

Metals to be Mixed.

Only the purest of metals should be used in these alloys. The cheaper grades of all metals contain impurities which are liable to spoil all the better qualities possessed by the metal. Scrap of an unknown composition, or of unknown methods in previous heat treatments should not be used.

In automobile work perhaps the most perfect alloys for bearing metals that can be produced are in use. No expense or labor is saved if it is possible in any way to improve the alloys for bearing purposes. The prevailing practice at present is to use on the crank shaft and connecting rod of the engine a hard phosphor bronze bearing composed of from 80 to 90 per cent copper, from 10 to 20 per cent of tin and sometimes from 0.25 to 2 per cent zinc with a corresponding reduction in the tin component. Copper-phosphide is usually used in treating the zinc, thus reducing the zinc oxides which, if left in the metal, would produce zones of brittleness after solidifying.

Zinc, however, should not be used where closely defined mechanical properties are desired. The following table shows the mechanical properties of the copper-tin-phosphor bronzes:-

Grade	Component of tin Per cent	Tensile Strength Lbs.	Elastic Limit Lbs	Elongation in 2" m Per Cent
Extra hard	20	28,000	28,000	--
Extra hard	18	33,000	27,000	--
Very hard	16	40,000	26,000	1
Very hard	14	41,000	25,500	2
Hard	12	44,000	24,000	5
Hard	10	47,000	22,000	9

Bearings Containing a High Percentage of Lead.

Bronzes, containing lead are not so commonly used as the ones just discussed. There is, however, some demand

for them and when used the proportions are about as follows: copper 65 per cent, lead 30 per cent and tin 5 per cent. Considerable care must be exercised on the part of the foundryman in order to produce a homogenous alloy. The tendency is for the lead to cool more rapidly than the copper thus producing segregation. The addition of 1 per cent of nickel will aid greatly in preventing segregation. Lead bronzes will take a high polish and not wear much as the lead separates from the alloy and forms on the surface. They possess better anti-frictional qualities than the phosphor-bronzes and are applicable only when low unit pressures are employed.

High-Friction Bearings.

For bearings which have to withstand very little pressure and a large amount of friction, the standard United States Government anti-friction bearing is about as good as any thing that is made. Its composition is 88.8 per cent tin, 3.7 per cent copper and 7.5 per cent antimony well fluxed with borax and rosin in mixing. It should be cast vertically. Where this alloy has failed it has in nearly every case been shown by chemical analysis that lead has been substituted for tin, or that zinc was one of the components.

By a study of the ingredients a careful mixing of them, the use of no scrap, not cooking the metal, and care exercised in moulding and pouring the cast bearings any foundry can turn out bearings that will stand the friction or bearing bronzes that will stand the heavy loads and hard

thrusts demanded by the automobile trade, and if they will stand the wear and shock stresses of the automobile they will be suitable for nearly every other line of machinery.

Alloys for Railroad Bearings.

In the early days of railroading before the time of high speeds and heavy loads the alloys used for bearings were those which had been adapted in general machine construction. The alloy in general use at this time was formed of copper and tin. The addition of tin to copper hardened the mixture and consequently as much tin as possible was added. The proportions varied from 80 per cent copper and 20 per cent tin to 90 per cent copper and 10 per cent tin. For a long time 87.5 per cent copper and 12.5 per cent tin was the standard and these percentages are still specified by some railroads. This alloy is, however, expensive and when used as a bearing heats rapidly owing to its hard and unyielding nature. To overcome this last defect, the bearing was lined with a thin coat of lead. This proved highly satisfactory because of the less tendency to heat and also because the bearings were easy to fit to the journal.

Another alloy very extensively used in railroad bearings about the year 1890 was copper and tin with the addition of lead and phosphorus. This alloy was known as the "S" brand and was adapted as the standard bearing at that time for the Pennsylvania railroad. It was found out experimentally that the addition of the lead to the copper and tin was of material benefit both in wearing and anti-frictional

qualities. Phosphorus being a deoxidizing agent and having the property of rendering the metal exceedingly fluid was added for its beneficial influence in the foundry. The specifications for this alloy were:

Copper - - - - 78 to 80 per cent

Lead - - - - - 8 to 11 per cent

Tin - - - - - - 9 to 11 per cent

Phosphorus - - 0.7 to 1 per cent

Impurities - - Not 0.33 per cent

The beneficial influence of lead having been noted it was a question as to how much lead should be added and also what relation the quantity of tin had upon the properties of the alloy. Experimentally the following facts were established: (1) Wear diminished with the increase of lead; (2) wear diminished with the diminution of tin; (3) the tendency to become heated decreases as the lead increases and the tin decreases.

These facts having been established the question arose as to how far could the decrease of tin and the increase of lead be extended and still maintain sufficient compressive strength so that the bearings would not distort under the load. After a good deal of experimenting the alloy containing the following proportions was adapted:

Tin - - - - - - - 5 per cent

Lead - - - - - 30 per cent

Copper - - - - 65 per cent

This alloy is known as "plastic bronze". It has

a compressive strength of about 15,000 lbs. per square inch and is found to work satisfactorily on the bearings of the heaviest locomotives in service. It is also used for rod brasses and bushings where considerable thrust is encountered. It finds extensive use also for bearings on cars of large capacity.

Besides the alloys here mentioned there are a number of other compositions described in specifications of various railroads. These specifications all cover alloys with tin from 8 to 10 per cent, lead from 10 to 15 per cent, with various details as to limitations of the various metals and impurities. A great many bearings are made entirely from scrap. Such bearings have approximately the following composition:-

Copper - - - -	65 to 75 per cent
Tin - - - - - - -	2 to 8 per cent
Lead - - - - -	10 to 18 per cent
Zinc - - - - - -	5 to 20 per cent

From 50 to 75 per cent of bearings for cars are made from scrap. For engine bearings a great deal more care should be taken and only alloys of approved composition should be taken. Within the past few years there has been a tendency to use scrap of unknown composition even for engine bearings. This is due to the high price of metals.

SUBJECTS SUGGESTED FOR FURTHER INVESTIGATION AND STUDY.

1 The determination of the following properties of the various standard bearing alloys with a complete discussion of the results.

(a) Chemical composition

(b) Microstructure

(c) Hardness

(d) Resistance to crushing

(e) Elastic tension

(f) Tensile strength

(g) Compressive strength

(h) Resistance to wear

(i) Resistance to heating

(j) Temperature at which molecular tension is overcome

(k) Anti-friction quality

(l) Coefficient of friction

Lubricated surfaces

Greasy surfaces

Unlubricated surfaces

(m) Variation of (l) for different pressures and speeds

(n) Cost

2 Influence of the material comprising the journal upon the coefficient of friction. (For lubricated surfaces only).

3 Determine the maximum pressure together with highest temperature at which bearing will work satisfactorily.

4 The effect of lengthening the journal upon the temperature. Load constant. Unit load varying.

5 Prove experimentally the formula $l = \dfrac{P}{40 d^{\frac{5}{4}} N^{\frac{1}{4}}}$

6 Prove experimentally the correctness of the formula $l =$

$\dfrac{P}{40\ d^{\frac{5}{4}}\ N^{\frac{1}{4}}}$ for speeds beyond 10 feet per second.

7 Working out a more general formula for the design of bear-

ings than the one just given. (Applicable for high as well as low speeds)

8 Determining the pressures and speeds at which the oil film breaks down for the various commercial oils.

9 What is the general effect upon the bearing of the various shape and arrangement of the oil grooves?

10 To determine the coefficient of viscosity for the various commercial oils.

11 To determine the value of a coefficient of radiation for bearings.

12 The effect of rotating pieces (flywheels for example) upon bearings near which such parts are located.

13 To determine what factor of safety should be used in formula $\frac{p_c}{p} = n$.

14 To determine the intensity of pressure at various points in the surface of a bearing.

15 To determine power required to overcome journal friction alone in various machine tools.

16 Investigate fully the method of designing bearings as given in Part I.

17 To test cubes of bearing metal in a machine similar to a brick testing machine (abrasion);

18 To determine the effect of the variation of pressure in a bearing due to eccentric loading.

19 To determine the correct clearance allowances for bearings.

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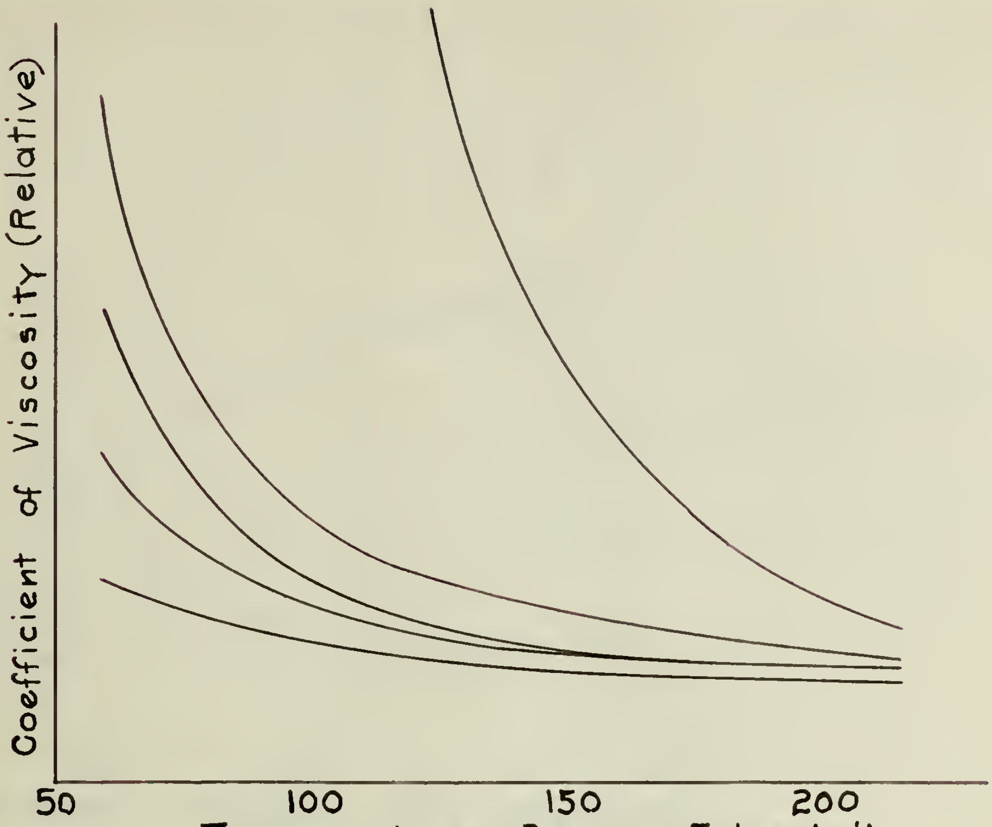


FIGURE 1

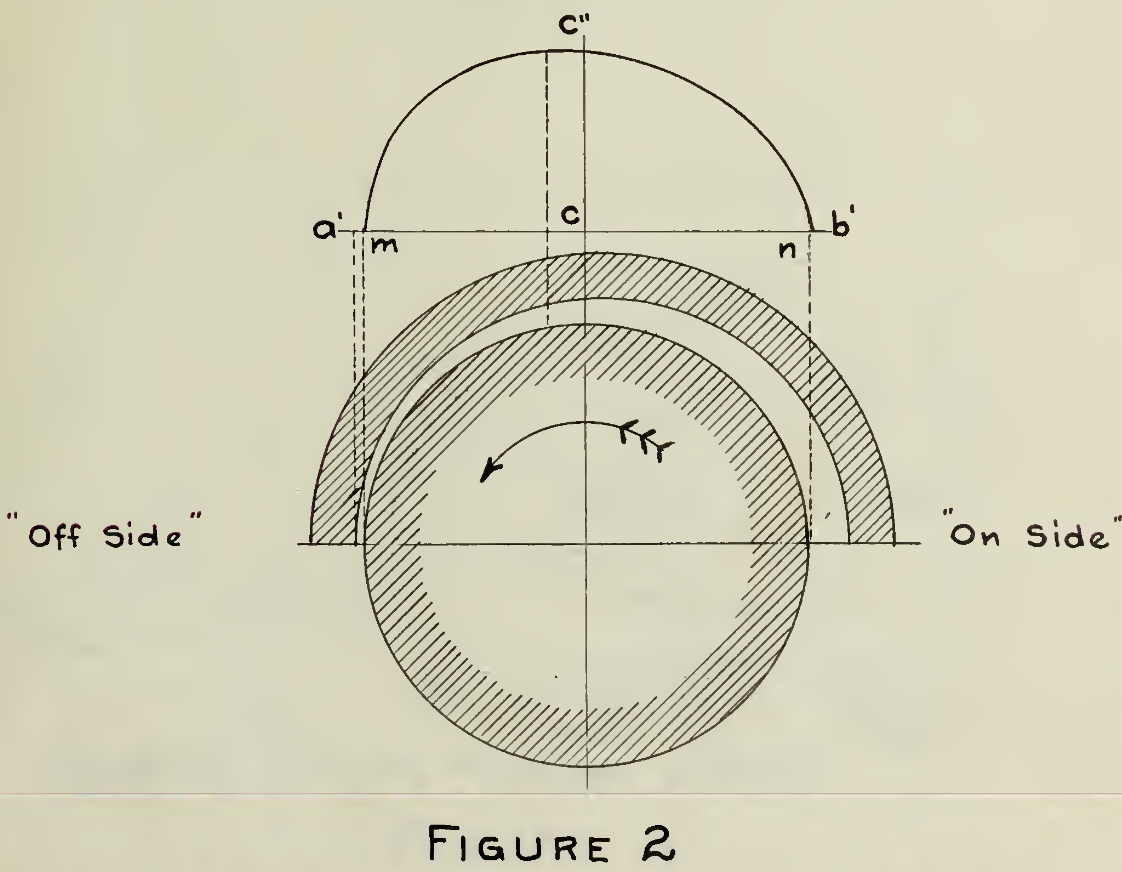


FIGURE 2

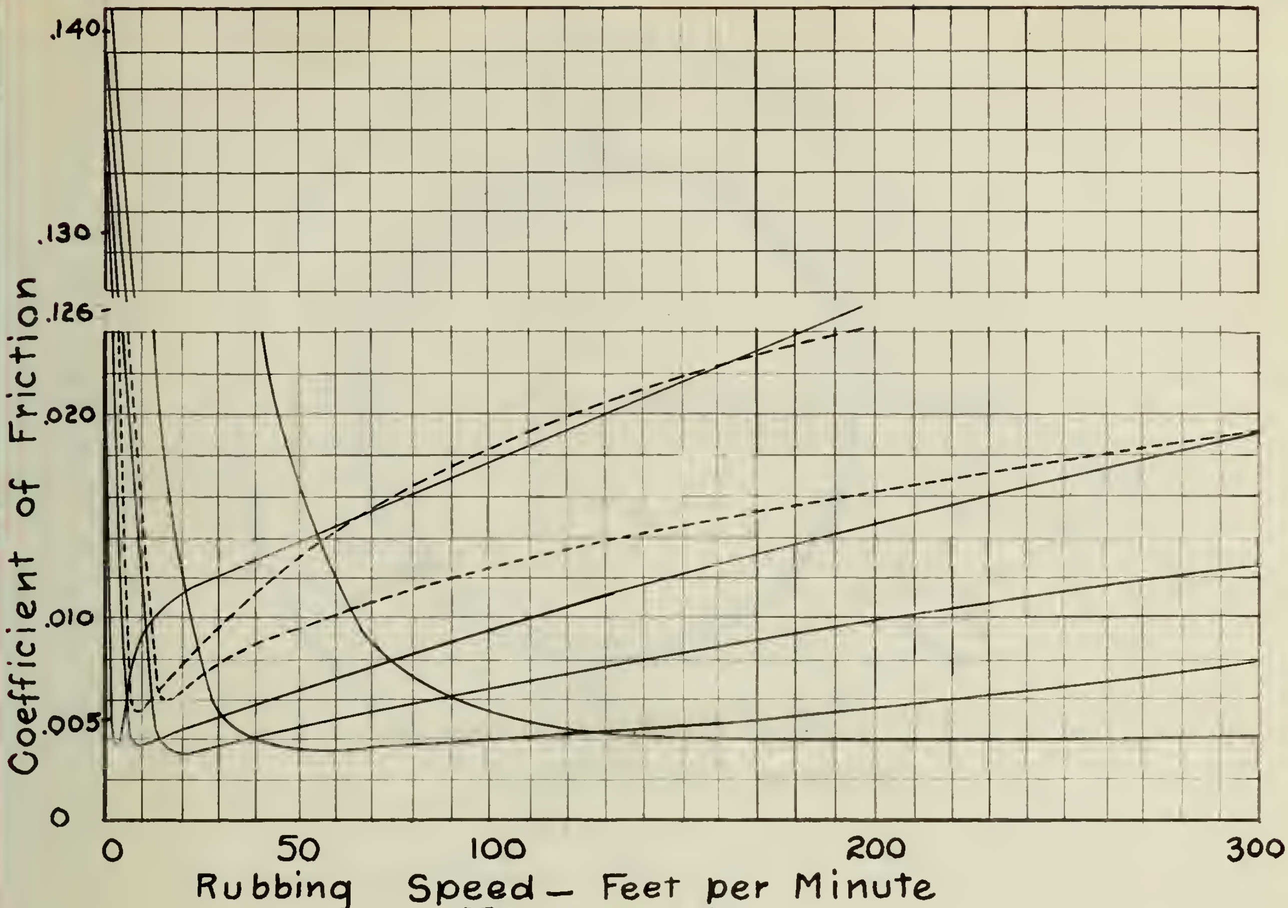
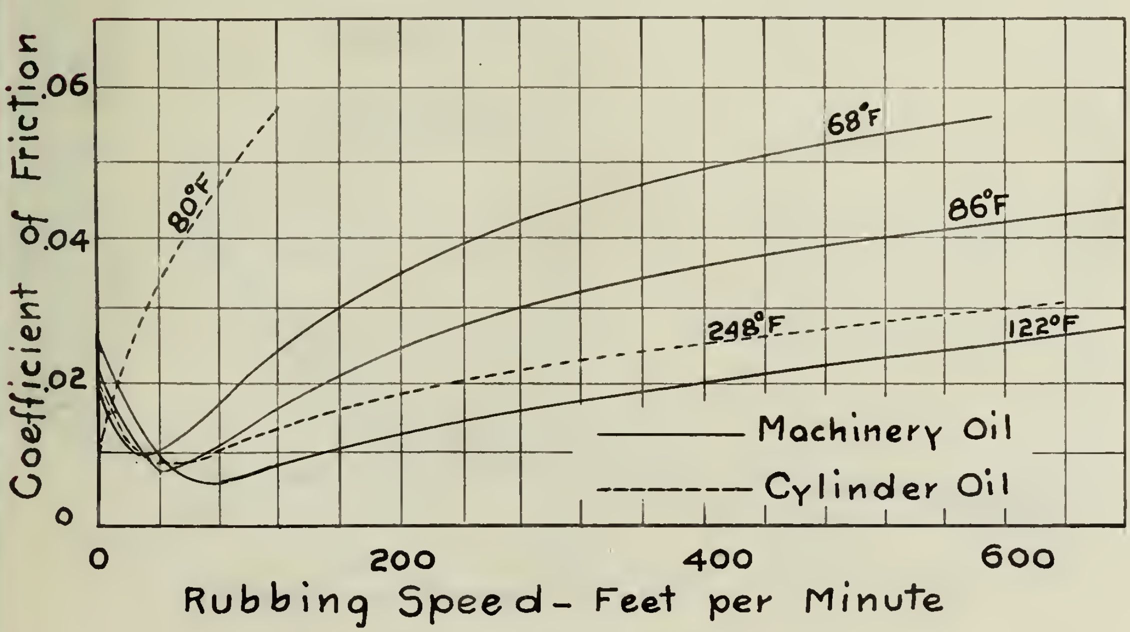


FIGURE 3



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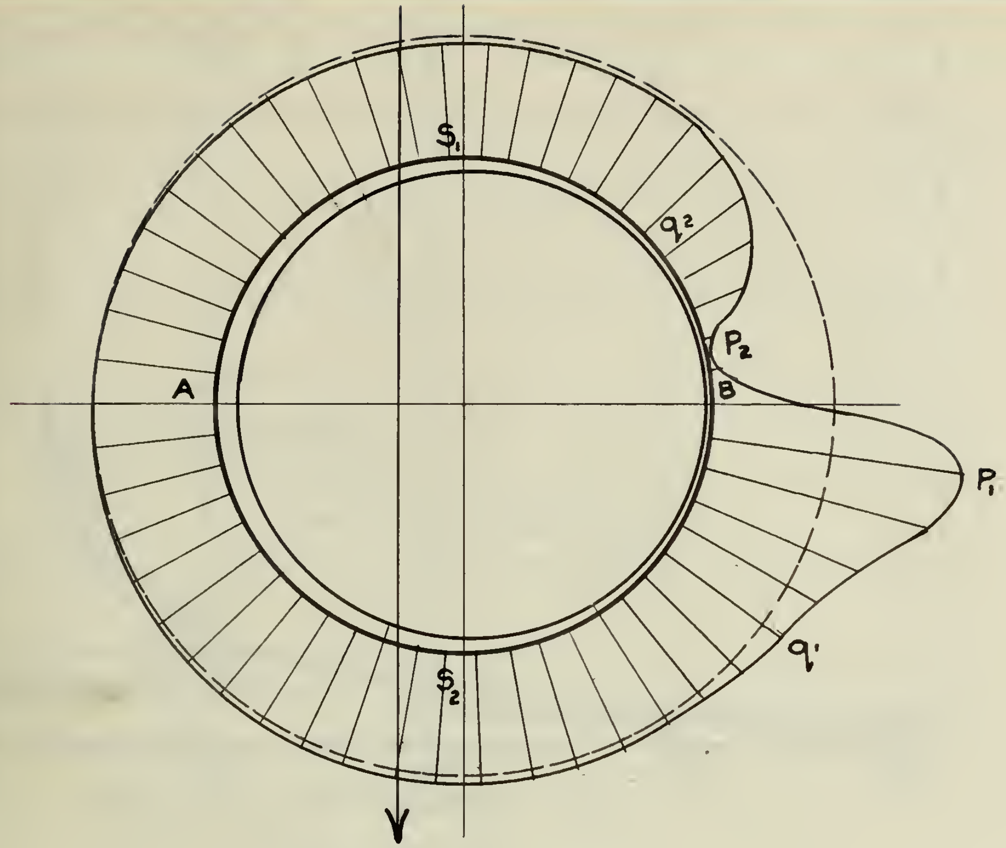
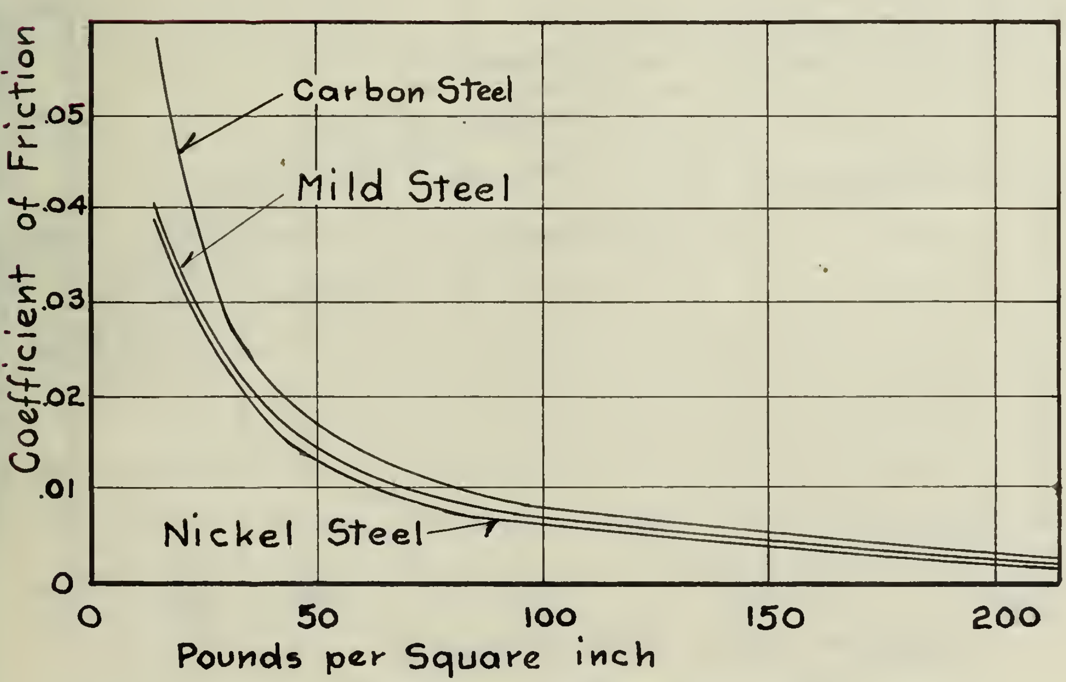


FIGURE 5



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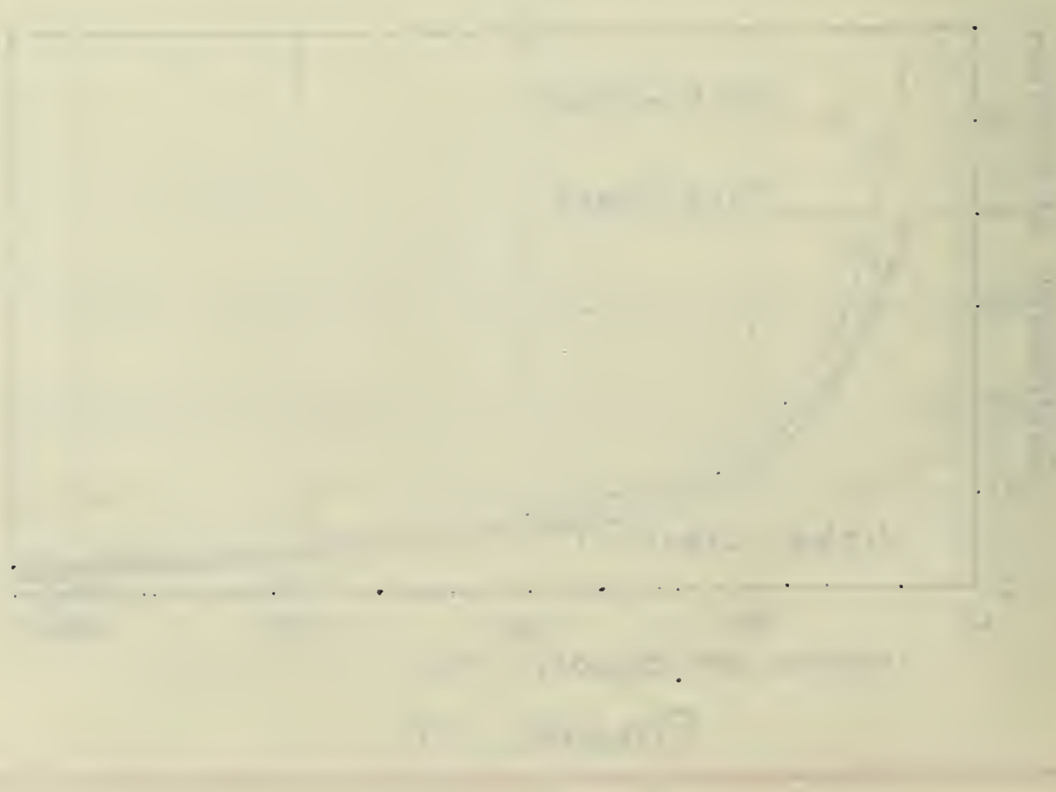

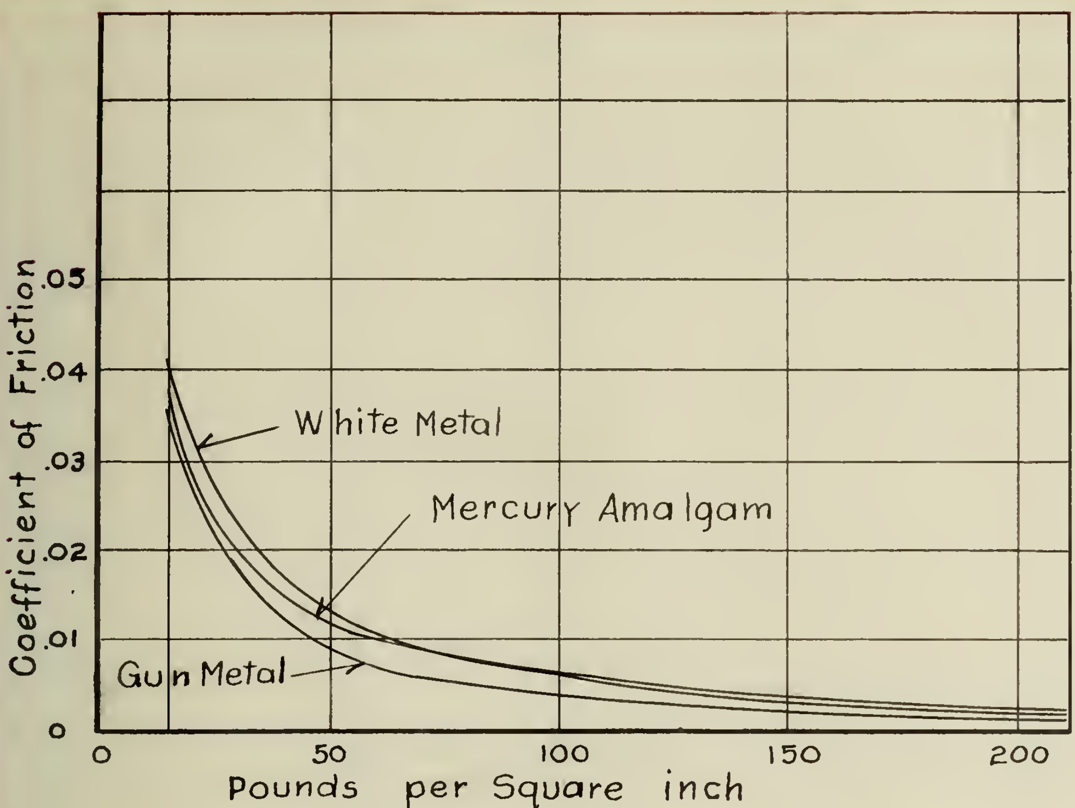

FIGURE 6

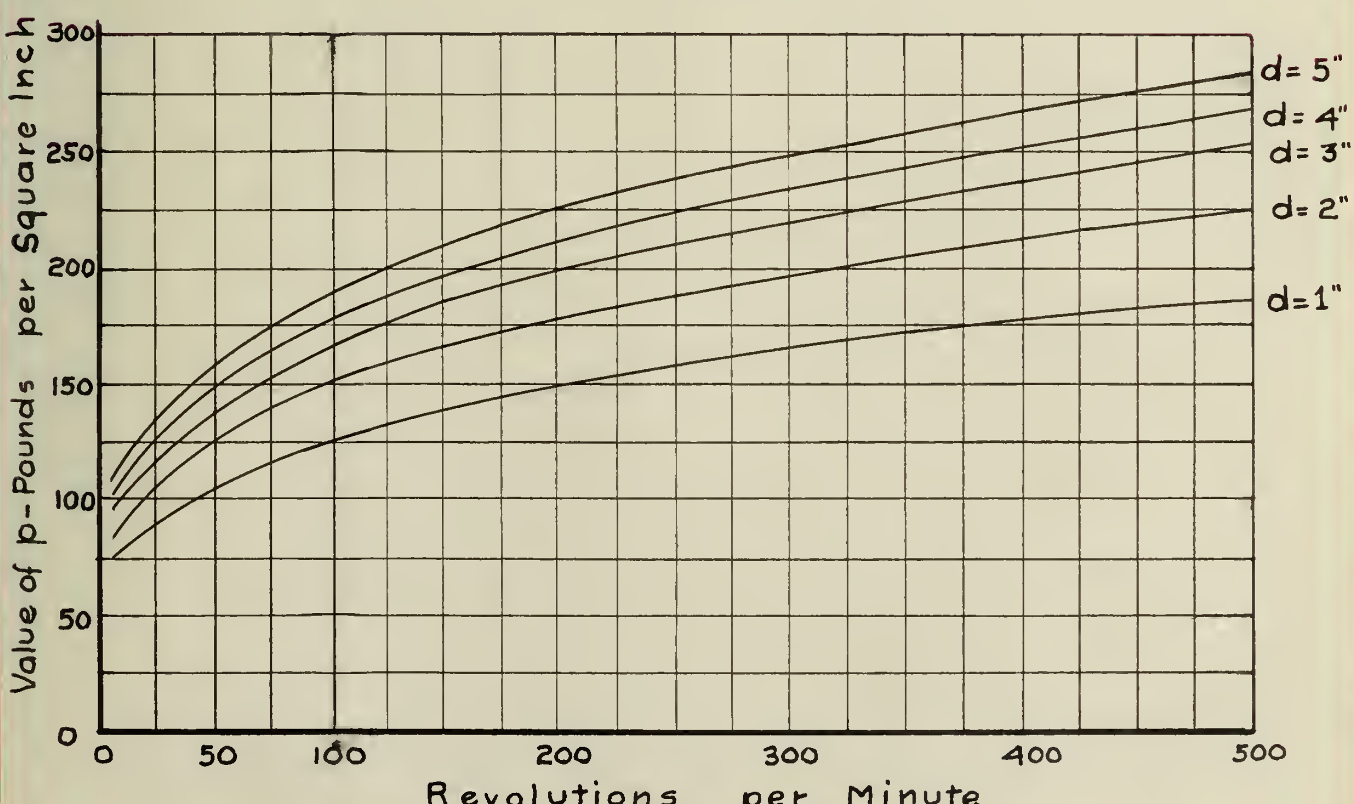

FIGURE 8